Appendix A Supplementary Material

A.1 Indoor Air Pollutants and Their Impact on Health

Indoor air pollution is caused by the degradation of indoor air quality due to harmful chemicals and substances, which can be more severe than outdoor pollution. The side effects of indoor air pollution are shown in statistical figures. In 2010, solid fuel combustion contributed to 16% of particulate matter to indoor pollution, resulting in 3.5 million deaths and accounting for 4.5% of global daily-adjusted life years (DALYs) [15]. The health status of students and employees is at risk due to varying harmful levels of formaldehyde, TVOC, CO, and PM [16]. Furthermore, oxides of nitrogen and formaldehydes may trigger respiratory illnesses [17].

These pollutants can be generalized into four overarching categories. Gaseous pollutants such as nitrogen oxides, sulfur dioxide, ozone, carbon monoxide, and ammonia contribute majorly to indoor air pollution and are common in urban households. Common sources of these gases include combustion fuels, construction materials, furnishings, heating and cooling systems, and air distribution channels [18]. Besides these, volatile organic compounds, also known as VOCs, are chemicals released in the air as a result of emissions from specific liquids and solids. A very common VOC is formaldehyde, a colorless gas with an unpleasant odor. It is released by plywood, particle board, and construction adhesives [19]. Short-term exposure to VOCs has not been shown to be particularly harmful, whereas long-term exposure raises health concerns for humans [20].

Radon has emerged as a major environmental carcinogen among other indoor pollutants. Its radioactive gaseous nature and multiple studies prove it as the second leading cause of lung cancer and its strong association with lung cancer cases [21]. Among those who are not susceptible to cigarette smoke or are not active smokers, 25% of lung cancer cases belong to such people. These patients have been affected by passive environmental carcinogens, mainly radon. Conclusively, radon exposure largely increases the tumor mutation burden (TMB), in contrast to smoking induced lung malignancies that are brought on by tobacco related mutations [15]. Its prevalence in indoor air environments is due to uranium breakdown occurring in soil and stone that seeps into indoor areas through cracks and builds up in concentration overtime [22]. Its radioactive properties suggest that during particle decay, the emission of alpha particles causes damage to DNA information, promote DNA mutations and leads to genomic instability raising cancer risk [22, 23]. A research study focusing on lung adenocarcinoma patients indicated that individuals exposed to higher radon levels showed an increased TMB (mean 4.94 mutations/Mb) when compared to those with lower exposure (2.6 mutations/Mb), and this finding was statistically significant ($p = 0.01$) [24]. As extended radon exposure is gradual, for every 100 Bq/m^3 increase in radon concentration, the risk of lung cancer increases by about 16%. However, even low exposures eventually raises the risk as radon exposure follows a linear no threshold model.

Particulate matter (PM), which is a mixture of carbonaceous particles, reactive metals, and organic compounds, is the most alarming component of indoor air pollution. Particulate matter (PM) is more common in indoor environments than outdoors. According to its particle size, it is divided into three categories: PM_{10} ($<10\ \mu$m), $PM_{2.5}$ ($<2.5\ \mu$m), and PM0.1 (¡0.1μ m). PM has a very fine nature that allows it to penetrate deep into the lungs, affecting both the respiratory and cardiovascular systems [25, 26]. Activities like cooking, cleaning, and smoking contribute majorly to indoor PM levels [21]. Smoking particularly raises $PM_2.5$ concentrations to 25–45 μg/m^3 [27].

Finally, biological contaminants, while not the greatest contributors, also have an impact, and these still include living organisms that irritate skin, such as dust mites, alongside pet cat and dog dander, pollen, and even viruses, fungi, and bacteria [28].

A.2 Sources, Mechanisms, and Environmental Influences on Indoor Air Quality

With the increasing attention being paid to indoor air quality degradation, factors affecting it — particularly environmental factors such as temperature, humidity, natural ventilation and urban factors — have also gained notice. Ever since WHO declared the sick building syndrome three decades ago, which is a condition describing occupants' acute health or discomfort related conditions with unexplainable diagnosis other than the time spent inside the building, indoor air quality (IAQ) has been highlighted as a central public health concern especially in homes and office spaces[29].

Indoor temperature significantly affects health, cognitive functioning, and infection rates. Temperature varying from room temperature at 26-27°C results in acute symptoms. While lower temperatures raise cardiovascular morbidity, higher temperatures contribute to dry eyes and respiratory problems [30, 31]. Zhang et al notes that cognitive functioning are at peak between temperatures ranging from 22°C to 24°C and experiences decline outside this range [32]. Furthermore, survival of certain respiratory viruses is easier at lower temperatures, although majority of the viruses become dormant when exposed to a heated environment for more than 60 minutes [33]. Beyond cognitive performance, thermal discomfort reduces work efficiency. Warmer indoor conditions also impair sleep quality which contributes to long-term health issues [34].

Indoor humidity has a significant impact on the occupants' health, however it is often ignored as an important factor. When indoor relative humidity drops below 30%, the precorneal tear film becomes destabilized, leading to increased dry eye symptoms and discomfort [35]. On the other hand, increased ideal humidity of about 40-60% lowers these symptoms [35]. Low humidity also hinders mucociliary clearance, exposing more people to infections and pollutants [36]. Notably, achieving ideal humidity levels disallows airborne pathogens such as influenza to fester and infect the people [37].

The above natural factors can be regulated better with efficient ventilation as it is essential for maintaining indoor air quality. Inadequate ventilation instead increases pollutant concentrations having much less desired effects. It is necessary for an average person to maintain a minimum breathing rate of 6-7 L/s to prevent acute health risks [38]. CO_2 levels greater than 1000 ppm impair cognitive function [39]. Moreover, Li et al [40], also warn of the increased viral transmission due to insufficient ventilation.

In Pakistan, more specifically, biomass burning remains a prevalent source of fuel in rural and partially urban areas. It is a significant contributor to indoor air health being damaged. Studies show that kitchens relying on wood fuels report average daytime CO concentrations of 29.4 ppm and $PM_2.5$ levels as high as 2.74 mg/m^3, with peak particulate concentrations while cooking reaching between 4,000 and 8,555 $\mu g/m^3$ [41]. Exposure to such harmful levels of particulate matter disproportionately affects women and children. A study documented a 2.6% increase in acute respiratory infection in children exposed to the fumes of biomass burning due to cooking [42]. Natural ventilation suffers greatly in Pakistan due to poor household infrastructure such as improperly located or smaller sized windows, lack of cross ventilation, enclosed kitchens, and multi-purpose cooking space. Poor indoor air quality has been closely linked to limited airflow in such an environment, with pollutants produced in the daily cooking and heating processes unable to be dispersed [43]. Research indicates that in addition to worsening asthma and other respiratory related issues poor ventilation causes an increase in carbon dioxide, carbon monoxide, and fine particulate matter ($PM_2.5$, PM_10) all of which are above the exposure limits that are considered safe [44, 45]. Under such circumstances, vulnerable groups such as children, as well as those who have co-occurring respiratory challenges are the most affected health wise. Moreover, the structural limitations such as poorly designed windows and few ventilation holes, limit the air exchange further, trapping contaminants in the building and increasing the long-term health hazard [46]. These results highlight the necessity of the housing design being ventilation-conscious in Pakistan.

Industrial and urban emission has impacted indoor air quality largely. This is exemplified by a study carried out in Taranto, Italy and in Spain, in which the results beared showed that while NO concentration mainly increased due to traffic, SO emissions were associated from industrial waste [47]. Benzene concentrations were highest in the industrial regions due to petrochemical activities. Additionally, Spanish institutes identified formaldehyde and hexanal as common indoor air pollutants [48]. The application of Radiello passive samplers for data acquisition indicated that despite VOCs being primarily sourced from indoor origins, NO levels are predominantly determined by external sources.

A.3 Plant-Based and Natural Strategies for Indoor Air Purification

Mitigating indoor air pollutants is crucial in producing a healthier indoor environment due to their detrimental effects. A three-step approach is effective: first, monitoring IAQ in real time and comparing it with WHO guidelines [30], identifying pollutant sources, such as moisture sealing and ventilation issues [15]; and third, reducing pollutant concentrations using sustainable methods. Although the mechanisms underlying plant-based phytoremediation are still unclear, it can improve the air quality [49]. The idea of using plants to improve IAQ originated with early studies such as the NASA Clean Air Study. Plants have been shown to absorb pollutants like VOCs (e.g., benzene, formaldehyde, and trichloroethylene) through their leaves and roots. Although controlled studies in sealed environments have been promising, research in real-world settings—such as tropical office environments—indicates that while measurable effects may be diluted, overall occupant well-being can still benefit. Additionally, alternative natural methods (for example, the use of microalgae to remove carbon monoxide) are also emerging as innovative, low-energy solutions for mitigating indoor pollutants.

Plant-based indoor air purification occurs as a result of certain physiological processes and bio chemical reactions carried out by the plants. Studies suggest that the removal of volatile organic compounds(VOCs) and other gaseous contaminants via absorption through the stomata, cuticular surface of the leaf, and plant-microbe interaction [2, 50]. Gaseous exchange, a primary physiological process during daylight hours, allows for the uptake of many indoor air pollutants. The most common is carbon dioxide which accumulates in the air spaces inside the leaf as it is a key component of photosynthesis. Alongside CO_2, nitrogen oxides, are also taken in. Many researches show that assimilation of atmospheric NOx reduces their concentration in the air and provides surplus of nitrogen to plants besides through nitrogen fixating bacteria [51, 52]. VOCs may also be absorbed during photosynthesis, where they are subsequently degraded into NO and water by phyllosphere microorganisms or metabolized through the Calvin Cycle [53]. Furthermore, some researchers also suggest root microbe interactions in the rhizosphere to be the main process of VOC degradation. Cuticular absorption also contributes, as evidenced by the concentrations of VOCs found in the waxy layer found on the upper surface of leaves and on some stems [54](weyenes). Conclusively, plant-microbe interactions have proven to be the most prevalent when observing phytoremediation. Due to this reason, the soil in the potted plants for this experiment is left uncovered.

In addition to these mechanisms, Crassulacean Acid Metabolism (CAM) plants perform an active role in air purification not only throughout the day but during the night as well. CAM species such as Aloe vera and Dracenea Trifaciata show nocturnal behaviors although being diurnal in nature. They exhibit opening of the stomata during the night to perform gaseous exchange especially CO_2 and VOCs [5]. This physiological adaptation enables CAM plants to contribute to air purification even during nighttime hours when most other plant species cease gaseous exchange. Studies indicate that CAM plants can significantly reduce total volatile organic compounds (TVOCs) and maintain more stable nighttime indoor air quality levels by sustaining low-level metabolic uptake and releasing oxygen through malic acid decarboxylation [55, 56].

In addition to their biological capabilities, plants can be incorporated into indoor environments as an alternative air quality intervention. The number of plants, the leaf surface area and plant spatial patterns affect purification of indoor air quality via pollutant removal. No matter the difference between true world impact and laboratory experiments, multiple studies suggest the addition of plants improves occupant health. This inclusion of plants comes in the forms of innovative structures with the likes of green wall integration for maximum surface area efficiency or suggested active biofilter designs [57–59]. Furthermore, optimizing plant performance by using low maintenance plants and catering their need of light energy holds potential for being a sufficient mechanism for air purification [60].

A.4 Synthesis of Literature Review Findings and Identified Gaps

The literature highlights need for a multifaceted approach to mitigating indoor air pollution in Pakistan. Key findings include:

Monitoring and Regulation: There is strong evidence for the benefits of real-time IAQ monitoring coupled with robust regulatory frameworks. However, achieving consistent compliance with WHO and local standards remains a significant challenge due to limited enforcement capacity and resource constraints.

Integrated Solutions: Because indoor pollutants originate from both internal sources (e.g., human activity, building materials) and external infiltration (e.g., smog, vehicular emissions), a holistic response is essential. Such strategies must combine improved natural and mechanical ventilation, source control, and innovative low-energy remediation methods, including plant-based phytoremediation supported by sensor-driven monitoring systems.

Quantitative Evaluation: While qualitative evidence of plant-based air purification benefits exists, further quantitative studies under real-world conditions are needed to assess measurable pollutant removal efficiency.

Mechanisms of Phytoremediation: The biochemical and microbial pathways through which plants absorb or degrade indoor pollutants remain incompletely understood and warrant deeper exploration.

External and Environmental Factors: Future studies should integrate outdoor AQI and satellite-based data with indoor sensor readings to build a comprehensive understanding of air quality dynamics, particularly under Lahore's seasonal smog conditions.

In conclusion, achieving healthier indoor environments in Pakistan requires a unified, data-driven approach that merges environmental monitoring, source control, and sustainable natural remediation technologies.

Table A1: Summary Table: Key Plant Species for Indoor Air Purification. Data for this table are based on controlled studies (NASA Clean Air Study [2]) and adapted considering local Pakistani environmental conditions as discussed in recent literature and MOCC guidelines [1, 3].

Plant Species	**Primary Pollutants Removed**	**Leaf Surface Area (cm^2)**	**Approximate Removal (μg/24h)**
Gerbera Daisy (Gerbera jamesonii)	Trichloroethylene (TCE)	$\sim 4,581$	$\sim 38,938$
English Ivy (Hedera helix)	Benzene, Formaldehyde	~ 981	Lower removal levels
Marginata (Dracaena marginata)	Benzene, TCE	$\sim 7,581$	$\sim 27,292$
Peace Lily (Spathiphyllum ”Mauna Loa”)	Formaldehyde, Benzene, TCE	$\sim 7,960$	$\sim 27,064$
Mother-in-law’s Tongue (Sansevieria laurentii)	Formaldehyde, Benzene	$\sim 3,474$	$\sim 9,727$
Bamboo Palm (Chamaedorea seifrizii)	General VOCs	$\sim 7,242$	$\sim 13,760$
Mass Cane (Dracaena massangeana)	Benzene, TCE	$\sim 10,325$	$\sim 16,520$
Janet Craig (Dracaena deremensis “Janet Craig”)	General VOCs	$\sim 7,215$	$\sim 18,330$

A.4.1 Indoor Plant Air Purification: A Quantitative Comparison

Table A2 summarizes key quantitative parameters comparing the effectiveness of indoor plants in two scenarios: rooms with proper ventilation versus rooms without ventilation. In ventilated spaces, where the air exchange rate is typically around 2.5–3 air changes per hour, a guideline of approximately one plant per 100 square feet (roughly 0.11 plants/m^2) can provide an additional volatile organic compound (VOC) reduction of about 10–15% (e.g. formaldehyde, benzene, trichloroethylene) when each plant contributes a clean air delivery rate (CADR) of around 0.062 m^3/hr [61, 62]. In contrast, in non-ventilated (sealed) rooms the lack of fresh air means that pollutants accumulate rapidly; studies indicate that to achieve even a modest improvement, one would require an impractical density (ranging from 10 to 1000 plants/m^2), and the effective VOC reduction may drop to below 5%. In addition, the relative humidity increase in sealed environments may rise by 10–20%, potentially promoting mould growth [62, 63].

Table A2 quantitatively compares key metrics for using indoor plants to improve air quality. In ventilated rooms, the recommended density of approximately one plant per 100 ft^2 (or about 0.11 plants/m^2) works in conjunction with 2.5–3 air changes per hour to yield an extra VOC reduction of roughly 10–15%, thanks to each plant’s CADR of about 0.062 m^3/hr [61, 62]. By contrast, in non-ventilated rooms, the absence of any air exchange results in rapid pollutant accumulation. Even if the same CADR is

Table A2: Comparison of Air-Purification Metrics in Ventilated vs. Non-Ventilated Rooms

Parameter	**Ventilated Rooms**	**Non-Ventilated Rooms**
Recommended Plant Density	≈0.11 plants/m^2 (1 per 100 ft^2) [61]	10–1000 plants/m^2 [62, 63]
Air Exchange Rate (ACH)	2.5–3 ACH [61]	0 ACH
Clean Air Delivery Rate per Plant	≈0.062 m^3/hr [61]	≈0.062 m^3/hr (ineffective) [61]
Additional VOC Reduction	10–15% [61, 62]	<5% [63]
Relative Humidity Increase	+5–10% [62]	+10–20% [62, 63]

assumed per plant, achieving a significant effect would require an impractically high plant density (10–1000 plants/m^2), and the overall VOC reduction drops below 5%. Moreover, the increase in relative humidity is higher (10–20%), which can lead to secondary issues such as mould growth [62, 63].

Parameter	**Ghazalli2012 (1 plant)**	**Ghazalli2012 (3 plants)**	**Ghazalli2012 (6 plants)**	**Ghazalli2012 (1 plant)**	**Ghazalli2012 (3 plants)**
Ventilation	Yes	Yes	Yes	Yes	Yes
Plant Used	Nephrolepis exaltata	Nephrolepis exaltata	Nephrolepis exaltata	Rhapis excelsa	Rhapis excelsa
Number of Plants	1	3	6	1	3
Measurement Duration & Frequency	8h (10-min intervals)	8h (10-min intervals)	8h (10-min intervals)	8h (10-min intervals)	8h (10-min intervals)
Test Room Dimension	0.3m x 0.5m x 0.3m	0.3m x 0.5m x 0.3m	0.3m x 0.5m x 0.3m	0.3m x 0.5m x 0.3m	0.3m x 0.5m x 0.3m
Mean Leaf Surface Area (cm^2)	–	–	–	–	–
Temperature (°C)	–	–	–	–	–
Pollutant Removed	VOCs	VOCs	VOCs	VOCs	VOCs
Removal Efficiency (%)	70–77%	74%	77%	63–75%	81%

Table A3: Summary of Ghazalli2012[64] Study on Plant-Based Air Purification (Transposed)

Table A4: Summary of Wolverton1984[65] study on plant-based air purification (transposed).

Parameter	**Spider Plant**	**Pothos**	**Golden Pothos**	**Nephtytis**
Ventilation	Non-ventilated	Non-ventilated	Non-ventilated	Non-ventilated
Plant Used	Spider Plant (Chlorophytum comosum)	Pothos (Epipremnum aureum)	Golden Pothos	Nephtytis
Number of Plants	1	1	2	2
Measurement Duration and Frequency	Continuous monitoring	Continuous monitoring	6 h	6 h
Test Chamber Dimension	Not specified	Not specified	0.733 x 0.733 x 0.733 m	0.733 x 0.733 x 0.733 m
Leaf Surface Area (cm^2)	7086	13083	9340	8549
Temperature (C)	20	20	20	20
Pollutant Removed	Formaldehyde	CO	Formaldehyde	Formaldehyde
Removal Efficiency	Significant reduction	96 percent or higher	0.61 ug cm^{-2}	0.67 ug cm^{-2}

Parameter	**Li2024 (Peace Lily)**	**Li2024 (Mother-in-law's Tongue)**	**Li2024 (Elatior Begonia)**	**Li2024 (Florist Kalanchoe)**
Ventilation	No	No	No	No
Plant Used	Peace Lily	Mother-in-law's Tongue	Elatior Begonia	Florist Kalanchoe
Number of Plants	1	1	1	1
Measurement Duration & Frequency	24h	24h	24h	24h
Test Room Dimension	0.8 x 0.8 x 0.8m	0.8 x 0.8 x 0.8m	0.8 x 0.8 x 0.8m	0.8 x 0.8 x 0.8m
Mean Leaf Surface Area (cm^2)	–	–	–	–
Temperature (°C)	23-25	23-25	23-25	23-25
Pollutant Removed	Benzene (C_6H_6)	Benzene (C_6H_6)	Benzene (C_6H_6)	Benzene (C_6H_6)
Removal Efficiency (%)	43.7%	42.4%	41.5%	38.9%

Table A5: Summary of Li2024[66] Study on Plant-Based Air Purification (Transposed)

Parameter	**Jiang2024 (5 Boston Ferns)**	**Jiang2024 (18 Boston Ferns)**
Ventilation	No	No
Plant Used	Boston Fern	Boston Fern
Number of Plants	5	18
Measurement Duration & Frequency	8.5h	8.5h
Test Room Dimension	28.8–33.4m	28.8–33.4m
Mean Leaf Surface Area (cm^2)	2247 ± 1.09	2247 ± 1.09
Temperature (°C)	23.4	23.21
Pollutant Removed	CO_2	CO_2
Removal Efficiency (%)	1.76%	1.92%

Table A6: Summary of Jiang2024[67] Study on Plant-Based Air Purification (Transposed)

Parameter	Wannomai2019 (Epipremnum aureum)	Wannomai2019 (Cereus hexagonus)
Ventilation	Closed fumigation	Closed fumigation
Plant Used	Epipremnum aureum (Linden et Andre) Bunting	Cereus hexagonus (L.) P. Mill.
Number of Plants	–	–
Measurement Duration & Frequency	72h	72h
Test Room Dimension	Not specified	Not specified
Mean Leaf Surface Area (cm^2)	–	–
Temperature (°C)	–	–
Pollutant Removed	VOCs	VOCs
Removal Efficiency (%)	45.3%	49.2%

Table A7: Summary of Wannomai2019[68] Study on Plant-Based Air Purification

.1 Carbon Sequestration Potential and Net Zero Analysis for BNU Campus

The assessment of carbon sequestration capacity represents a critical dimension of sustainable campus management, particularly in urban centers like Lahore where outdoor air quality severely constrains natural mitigation potential. To evaluate Beaconhouse National University's pathway toward carbon neutrality through integrated vegetation and renewable energy strategies, we calculated the net carbon balance using:

$$\text{Net Zero} = \text{GHGs}_{\text{emitted}} - \text{GHGs}_{\text{removed}} \tag{1}$$

where total emissions comprise electricity consumption and waste generation, while offsets include solar energy generation and vegetation-based carbon sequestration.

.1.1 Campus Carbon Footprint Analysis

Analysis of BNU's operational data from January through September 2024 revealed substantial carbon emissions primarily from electricity consumption. The campus consumed 656,000 units of grid electricity over nine months, generating 403,440 kg (95.76 tons) of CO_2 emissions. Monthly consumption patterns (Table 1) exhibited significant seasonal variation, with peak emissions during summer months: June recorded the highest consumption at 148,000 units (91.02 tons CO_2), while March showed minimal usage at 4,000 units (2.46 tons CO_2), reflecting the campus closure period.

Table 1: Monthly Grid Electricity Consumption and CO_2 Emissions (January–September 2024)

Month	Units (kWh)	CO_2 (kg)	CO_2 (tons)
January	80,000	49,200	49.20
February	20,000	12,300	12.30
March	4,000	2,460	2.46
April	76,000	46,740	46.74
May	116,000	71,340	71.34
June	148,000	91,020	91.02
July	64,000	39,360	39.36
August	56,000	34,440	34.44
September	92,000	56,580	56.58
Total (9 months)	**656,000**	**403,440**	**95.76**
Annualized	**874,667**	**537,920**	**127.68**

Note: Emission factor = 0.615 kg CO_2/kWh (Pakistan grid average)

Solar installations provided partial mitigation, generating 58,884 units over the same period and offsetting 36,219 kg (36.22 tons) of CO_2 emissions (Table 2). The solar contribution varied from 3,772 units in February to 9,027 units in April, demonstrating seasonal photovoltaic efficiency patterns typical of Pakistan's climate.

Waste management activities from April through September contributed an additional 13,940 kg (13.94 tons) of CO_2 emissions from bottles, glass, food waste, plastics,

Table 2: Solar Energy Generation and Carbon Offset (January–September 2024)

Month	Solar (kWh)	CO_2 Offset (kg)	Offset (tons)	Net (tons)
January	4,764	2,930	2.93	46.27
February	3,772	2,320	2.32	9.98
March	4,226	2,599	2.60	−0.14
April	9,027	5,552	5.55	41.19
May	8,445	5,194	5.19	66.15
June	7,414	4,560	4.56	86.46
July	6,950	4,274	4.27	35.09
August	6,674	4,105	4.11	30.34
September	7,612	4,682	4.68	51.90
Total (9 months)	**58,884**	**36,219**	**36.22**	**59.54**
Annualized	**78,512**	**48,292**	**48.29**	**79.39**

and cartons (Table 3). June exhibited peak waste emissions at 2.61 tons, correlating with maximum campus occupancy during examination periods.

Table 3: Waste-Related CO_2 Emissions (April–September 2024)

Month	Waste (kg)	CO_2 (kg)	CO_2 (tons)
April	84.50	204.65	0.20
May	294.26	563.20	0.56
June	1,065.27	2,609.80	2.61
July	620.08	2,414.74	2.41
August	1,164.34	1,732.82	1.73
September	583.93	2,165.67	2.17
Total (6 months)	**3,812.38**	**9,690.88**	**9.69**
Annualized	**7,624.76**	**19,381.76**	**19.38**

Annualizing the nine-month electricity data and six-month waste data yields:

$$\text{Annual grid emissions} = \frac{95.76\text{ tons}}{9\text{ months}} \times 12 = 127.68\text{ tons CO}_2 \tag{2}$$

$$\text{Annual solar offset} = \frac{36.22\text{ tons}}{9\text{ months}} \times 12 = 48.29\text{ tons CO}_2 \tag{3}$$

$$\text{Annual waste emissions} = \frac{9.69\text{ tons}}{6\text{ months}} \times 12 = 19.38\text{ tons CO}_2 \tag{4}$$

$$\text{Net annual emissions} = 127.68 - 48.29 + 19.38 = \mathbf{98.77\text{ tons CO}_2} \tag{5}$$

.1.2 Vegetation Inventory and Sequestration Capacity

BNU's campus supports 1,943 mature trees representing 37 species (Table 4) and 5,297 indoor/potted plants spanning 40 species (Table 5). The tree inventory includes significant carbon-sequestering species: Neem (*Azadirachta indica*, 90 specimens total), Bamboo (*Bambusoideae*, 120 specimens), Ficus species (105 specimens), and Kohno trees (102 specimens). The indoor collection features air-purifying species including Snake Plants (*Dracaena trifasciata*, 50 units), Spider Plants (*Chlorophytum comosum*, 50 units), Money Plants (*Epipremnum aureum*, 50 units), and Aloe Vera (30 units).

Table 4: BNU Campus Tree Inventory Summary (Top 15 Species)

No.	Species	Count	No.	Species	Count
1	Kohno	102	9	Kacnar	50
2	Bamboo	120	10	Jaman	45
3	King Ficus	100	11	Pilkan	40
4	Neem (var. 1)	50	12	Neem (var. 2)	40
5	Casia Fistola	30	13	Melaleuca	30
6	Bottle Brush	25	14	Terminalia	20
7	Lemon	15	15	Gul e Chin	15
8	Others (22 spp.)	306		**Total**	**1,943**

Table 5: BNU Campus Indoor/Potted Plant Inventory Summary (Top 15 Species)

No.	Species	Count	No.	Species	Count
1	Gardenia	1,000	9	Motia Desi	350
2	Bombay Creeper	400	10	Silvery	350
3	Merva Dwarf	300	11	Movi Fax	290
4	Pada Ficus	250	12	English Rose	250
5	Black Ficus	250	13	Bogan Vallia	200
6	Dry Cena	160	14	Golden Ficus	150
7	Bait Palm	150	15	Cain Palm	100
8	Others (25 spp.)	897		**Total**	**5,297**

Carbon sequestration rates for mature trees in tropical urban environments range from 21.77 to 48.00 kg CO_2/tree/year [15], with larger canopy species approaching the upper bound. Applying a conservative estimate of 25 kg CO_2/tree/year accounts for BNU's mixed-species composition and urban growth constraints:

$$\text{Tree sequestration} = 1,943 \times 25 = 48,575 \text{ kg/year} = 48.58 \text{ tons/year} \tag{6}$$

Indoor and potted plants exhibit substantially lower per-unit sequestration (0.9–5.0 kg CO_2/plant/year) due to biomass limitations [56, 60]. CAM plants (Snake Plant, Aloe Vera) sequester at the lower range but provide unique nighttime CO_2 reduction. Applying 1.5 kg CO_2/plant/year:

$$\text{Plant sequestration} = 5,297 \times 1.5 = 7,945.5 \text{ kg/year} = 7.95 \text{ tons/year} \tag{7}$$

$$\text{Total vegetation sequestration} = 48.58 + 7.95 = 56.53 \text{ tons } CO_2/\text{year} \tag{8}$$

.1.3 Net Carbon Balance and Carbon Neutrality Pathway

Table 6 presents BNU's comprehensive carbon accounting, integrating all emission sources and offset mechanisms.

Table 6: BNU Campus Carbon Footprint and Offset Analysis

Category	**Tons CO_2/year**	**% of Gross**
CARBON FOOTPRINT		
Grid Electricity Consumption	127.68	86.8
Waste Generation	19.38	13.2
Gross Emissions	**147.06**	**100.0**
CARBON OFFSETS		
Renewable Energy		
Solar Energy Generation	−48.29	32.8
Natural Sequestration		
Outdoor Trees (1,943 units @ 25 kg/yr)	−48.58	33.0
Indoor Plants (5,297 units @ 1.5 kg/yr)	−7.95	5.4
Total Offsets	**−104.82**	**71.2**
NET CARBON BALANCE		
Net Annual Emissions	**+42.24**	–
Current Offset Achievement	71.2%	–
Gap to Carbon Neutrality	28.8%	–

Note: Negative values indicate carbon reduction

The net carbon position reveals:

$$\text{Net Balance} = 147.06 - 104.82 = +42.24 \text{ tons } CO_2/\text{year} \tag{9}$$

BNU currently offsets 71.2% of its carbon footprint through combined renewable energy (32.8%) and vegetation (38.4%) strategies. To achieve carbon neutrality, the campus requires an additional 42.24 tons/year of offset capacity.

Table 8 presents three strategic pathways to close this emission gap.

.1.4 Strategic Implications and Recommendations

The analysis demonstrates that BNU has achieved substantial progress toward carbon neutrality, with existing infrastructure offsetting 71.2% of operational emissions. However, the remaining 42.24-ton gap requires strategic intervention. Key findings include:

Table 7: Simplified BNU Campus Carbon Footprint and Offset Summary

Category	CO_2 (tons/year)	Share (%)
1. Carbon Footprint		
Grid Electricity Consumption	127.68	86.8
Waste Generation	19.38	13.2
Total Emissions	**147.06**	**100.0**
2. Carbon Offsets		
Solar Energy Generation	−48.29	32.8
Outdoor Trees (1,943 units)	−48.58	33.0
Indoor Plants (5,297 units)	−7.95	5.4
Total Offsets	**−104.82**	**71.2**
3. Net Carbon Balance		
Net Annual Emissions	**42.24**	–
Current Offset Achievement	71.2%	–
Gap to Carbon Neutrality	28.8%	–

Note: Negative values indicate carbon reduction through offsets.

Table 8: Carbon Neutrality Pathways for BNU Campus

Scenario	Strategy	Add'l Units	Increase
1	Indoor/Potted Plants Only	28,160 plants	+531%
2	Outdoor Trees Only	1,690 trees	+87%
3	Hybrid (50%/50%)	845 trees + 14,080 plants	+43% / +266%
4	Solar Expansion Only	87,480 kWh/year	+111%

Calculations: (1) 42,240 kg ÷ 1.5 kg/plant; (2) 42,240 kg ÷ 25 kg/tree;

(3) Split equally; (4) 42,240 kg ÷ 0.615 kg/kWh × 1.22 (efficiency factor)

1. **Vegetation Impact:** The 1,943 trees provide 48.58 tons/year sequestration (33.0% of gross emissions), demonstrating the critical importance of mature tree preservation and expansion.
2. **Solar Contribution:** Current photovoltaic installations offset 48.29 tons/year (32.8%), nearly matching tree sequestration and representing the most cost-effective carbon reduction mechanism.
3. **Indoor Plants:** Despite comprising 5,297 units, indoor plants contribute only 7.95 tons/year (5.4%) due to biomass constraints. However, their dual benefit of air quality improvement (demonstrated in Sections 3.2–3.3) justifies continued deployment.
4. **Hybrid Pathway:** Scenario 3 offers practical implementation: adding 845 trees (+43%) and 14,080 plants (+266%) balances space constraints with carbon goals while maximizing indoor air quality co-benefits.
5. **Solar Priority:** Scenario 4 indicates that doubling solar capacity would achieve neutrality without vegetation expansion, suggesting renewable energy should be the primary carbon mitigation strategy.

The documented effectiveness of CAM species (Snake Plant, Aloe Vera) in nighttime CO_2 reduction (Section 3.3.4), combined with their proven particulate matter and VOC reduction capabilities, positions strategic indoor plant deployment as a high-value complementary strategy that delivers both carbon sequestration and occupant health benefits during Lahore's severe smog season [69, 70].