Limited access to air cleaning systems in low-income countries increases occupants' health risks

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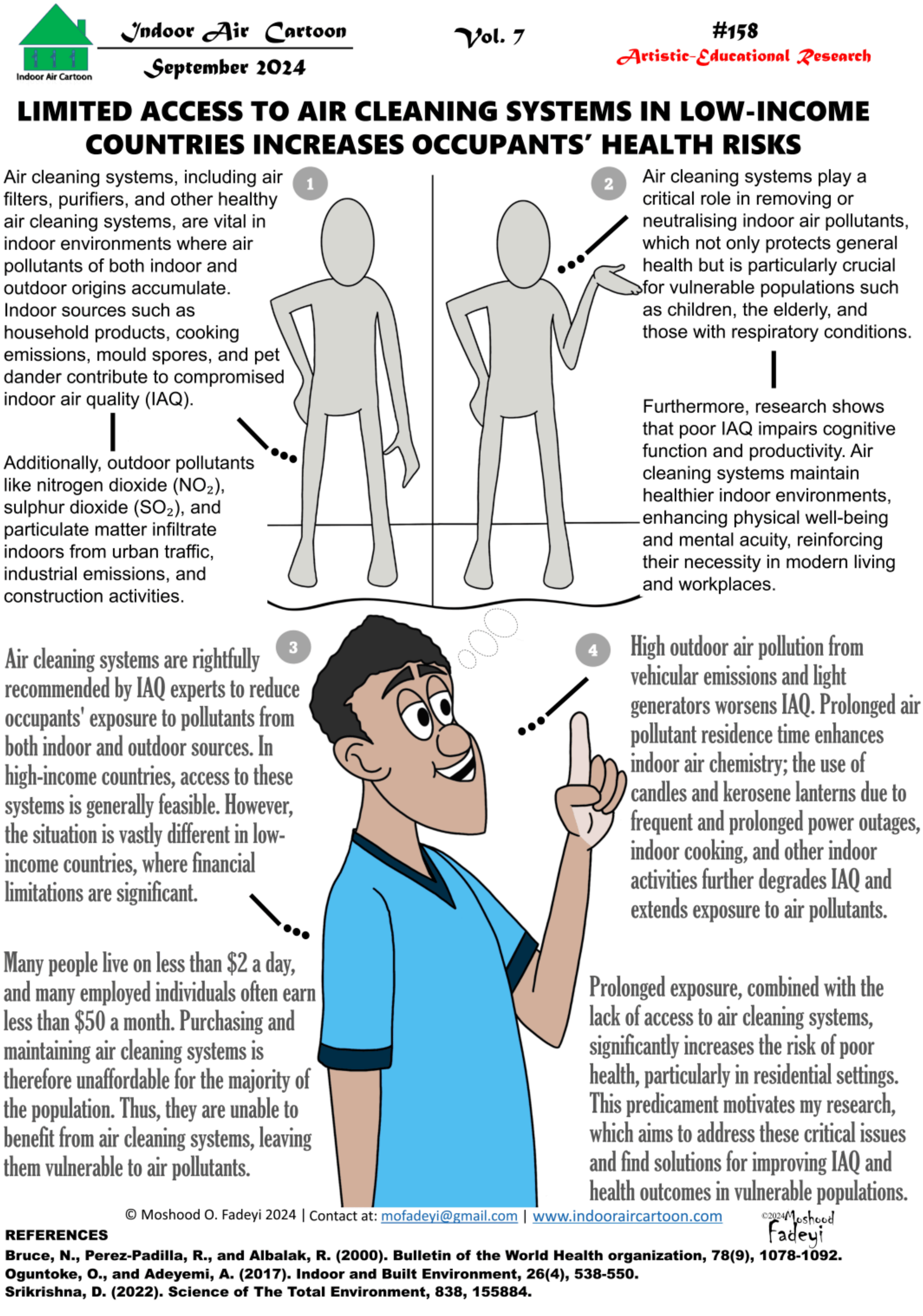

Fictional Case Story (Audio – available online) – Part 1

Fictional Case Story (Audio – available online) – Part 2

Fictional Case Story (Audio – available online) – Part 3

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The lack of protection from indoor air pollutants, originating from both indoor and outdoor environments, was leading to a rise in health problems in a low-income country. The situation worsened as exposure to these pollutants increased, compounded by limited access to air cleaning systems. With many people living on less than $2 a day, there was little motivation or means to obtain such systems. Unfortunate personal life events and struggles taught a man a valuable lesson—one that led him on a journey of conceiving the idea of developing an affordable solution to significantly reduce the health risks associated with poor indoor air quality. He led efforts to create a system that could be both procured and maintained at a price people in his country could afford. The journey of this man is the focus of this short fiction story.

1 ………………………………

My name is Malvin Martins. I was the firstborn of seven children, a responsibility that always weighed on me, though I did not realise how much until life forced me to bear it fully. My family lived in a small village in Pamsia, a low-income and tropical country where our parents farmed the land my father had inherited from his father and his father before him.

It was not much, but it had sustained us, and through their hard work, my parents ensured that my siblings and I could attend school. My parents believed that formal education was our path to a better future, one where we would not have to rely solely on the land for survival.

For as long as I could remember, I had wanted to attend university. I had just graduated from high school, a feat that my parents were immensely proud of, but we all knew it was only the first step. However, that dream was soon taken from me when the storm came.

Quite literally, it was a storm–one that washed away our crops, flooded our land, and left us with nothing but wet soil and debt. I can still see my father standing there, staring at the destruction in silence, his shoulders slumped, his spirit broken. He had spent years cultivating that land, and in just one night, it was all gone.

With our livelihood destroyed, the reality of our situation hit hard. We had no means of income, and my father, already ageing, could not imagine starting over again. My mother tried to find work, but there was none to be had in the village.

Soon, we struggled to afford even the basics–food became scarce, and schooling for my younger siblings seemed impossible. Every passing day felt heavier, and the weight on my chest grew as I watched my parents quietly despair, unable to provide for us as they always had.

I knew I had to do something. I had to step up, but there were no jobs in our village. People like us did not have many options, especially after our land was rendered useless. The only solution I could see was to leave. The thought of it terrified me, but I could not just stand by and watch my family suffer.

So, I made a decision. I would go overseas to one of the high-income countries, where the currency was stronger, and the wages, though meagre by their standards, would be a fortune back home. I figured if I could send money back, it would ease the pressure on my parents, help settle the mounting debts, and, most importantly, keep my siblings in school. I could not bear the thought of their education being interrupted, not after how hard our parents had worked to make sure we had that chance.

I found a construction job in Solterra through an employment agency in my country. The arrangement with the employment agency required that I pay them back with high interest for the service they provided in finding a job for me in Solterra and paying for my flight. I had no choice but to accept this arrangement, as there was no way I could source money myself.

My family and I were full of tears when the day came for me to travel. I did not have much when I left–just a small suitcase and the clothes on my back. The journey was long, filled with uncertainty and fear. I had no idea what to expect on the other side, only that I had to work hard to send money home to take care of my family and pay my debt.

I worked as a labourer, spending my days hauling heavy loads and doing the kind of work that left my hands hardened and my body aching. The pay was little, barely enough for me to live on in this expensive country, but I sent home 90% of it. My family needed it more than I did. I endured the long hours, the backbreaking labour, and the loneliness because I had no other choice. I had to keep going for them.

Sometimes, late at night, when my body was too tired to sleep, I would think about what my life could have been if things had gone differently. I would think about the university I had dreamed of attending, about the career I had hoped to build. But those thoughts never lingered long. What kept me going was the knowledge that my siblings were still in school, that they would not have to give up their education like I did. And that was enough for me to keep going, no matter how much I suffered.

Six years had passed since I first arrived in this foreign land, my hands still rough from the unrelenting work of a labourer. My days followed a monotonous routine–hauling bricks, mixing cement, and enduring the weight of tasks that wore down both body and spirit. Yet, no matter how gruelling the work, I always kept my family in mind, and that gave me strength. I had not seen my siblings in years, but I knew they were still in school because of the money I sent home each month. That alone made the sacrifices bearable.

One day, while I was on-site, the supervisor, Mr. Carter, approached me. He was a man I had seen many times, but like most people in positions of authority, he rarely spoke to workers like me unless there was a problem to address. To my surprise, he struck up a conversation. “Your English is quite good,” he said, leaning against a stack of bricks. I nodded, not knowing what to say at first. Compliments were not something I was used to in this line of work.

“Thank you, sir,” I replied. He raised an eyebrow, seeming intrigued by my response. “Where did you learn to speak like that?” I hesitated for a moment, unsure if I should share my story. But something about Mr. Carter’s tone, his genuine curiosity, made me open up. I told him about my life in Pamsia, my parents, and our land. I told him about the storm that destroyed everything we had, forcing me to leave and seek work abroad. And finally, I told him about my education–how I had finished high school with the dream of going to university, but that dream had been sacrificed for the sake of my family.

As I spoke, I could see Mr. Carter's expression soften, his initial curiosity shifting to something deeper. He listened intently, asking thoughtful questions that made me realise he was not just being polite–he genuinely wanted to know my story.

"And you wanted to go to university?" he asked, as if trying to imagine me in a classroom instead of on a construction site. "Yes," I admitted. "That was my goal. But, well, life had other plans." For a moment, he did not say anything. He just looked at me, as if trying to reconcile the image of the labourer in front of him with the aspirations I had just laid bare.

"You are too smart for this work," he finally said, his voice low but certain. "You do not belong here, hauling bricks. You have potential–anyone can see that." I did not know how to respond. No one had ever told me I had potential, not since I had left home. I had buried those thoughts deep, focusing only on survival and sending money back to my family. "Have you ever thought about continuing your education?" he asked. "Here?" I replied, shaking my head. "The universities will not even look at me. I do not have the qualifications, and even if I did, I could not afford the fees."

Mr. Carter thought for a moment, then leaned in a little closer. "You know, my children have gone through school here. If you want to attend university, you will need to pass the A-level examinations. That is the only way you can get considered for admission as an international student."

I had heard of the A-level exams but had dismissed them as something far beyond my reach. After all, I had not touched a textbook in years, and those exams were notoriously difficult. I told Mr. Carter as much, but he just shook his head.

"You are smart," he said firmly. "I had been watching you these past few years–you pick up things quickly, you are a problem solver, and your English is excellent. You are not just another labourer. If you study for these exams, I have no doubt you will pass."

His words filled me with a cautious hope, but I still could not ignore the practicalities. "Even if I could pass, I do not have the money to take the exams." Mr. Carter smiled slightly, as though he had anticipated my concern. "I will pay for the exam fees," he said. "And I will give you my kids' old A-level textbooks. You will need to put in the work, but I will make sure you have what you need to succeed."

For a moment, I could not speak. This man, someone I barely knew beyond the worksite, was offering to help me in ways I had not thought possible. I had been so focused on just surviving that I had forgotten what it felt like to dream, to imagine a life beyond this one.

"But why?" I finally managed to ask. "Why would you help me?" Mr. Carter's expression grew serious, his voice almost fatherly. "Because I see something in you. I had been in this business a long time, and I know when someone is wasting their potential. You are one of those people. I cannot stand by and watch someone like you stay stuck in this life when I know you can achieve so much more. All I ask is that you take this chance and make the most of it."

His words stayed with me long after he walked away, leaving me with a promise and the first glimmer of hope I had had in years. That night, I lay awake, staring at the ceiling of the small room I rented, imagining a future where I could step into a university, where my dreams could once again take root. Mr. Carter had opened a door for me, and all I had to do was step through it.

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I accepted Mr. Carter's offer without hesitation, though the enormity of it weighed heavily on my mind. I had spent six long years working on construction sites, my dreams buried beneath the endless cycle of lifting, hauling, and sweating under the unforgiving sun. But now, there was a spark–a glimmer of hope that my life could change. That maybe, just maybe, I could reclaim the future I had once dreamt of.

I registered for the A-level examinations in Solterra as a private international student. It was not easy–the cost of the registration was significant, but as promised, Mr. Carter covered the fees and gave me his children's old textbooks. Those books became my constant companions. My days were still filled with the backbreaking labour of construction work, but now, my nights belonged to studying.

Balancing work and study was not something I had anticipated would be this hard. Each day, I returned to my small, cramped room utterly exhausted, my muscles aching and my mind dulled by the long hours of labour. But I pushed through the fatigue, forcing myself to stay awake as I pored over equations, physics problems, and chemistry concepts.

I revisited subjects I had not touched in years, often feeling overwhelmed by how much I had to catch up on. There were many nights when I thought about quitting, when the burden of both work and study seemed impossible to bear.

But then, I would think of my family–my siblings, still in school, relying on the money I sent home; my parents, who had worked so hard to provide for us before everything was taken away. I had sacrificed so much for them, and now, they were my motivation to keep going. Every bit of progress I made was for them, so I could give them a better life, so they would not have to suffer like I had.

Months passed, and the day of the A-level exams finally arrived. I walked into the examination hall with a mix of fear and hope, knowing that my future depended on this moment. The tests were tough–harder than anything I had faced before–but I felt prepared. I gave everything I had, determined not to let this opportunity slip through my fingers. When I left the hall after the last exam, I felt an odd sense of calm. I had done all I could.

When the results came, I could not believe my eyes. I had aced the exams. Not just passed, but excelled. My scores were in the highest percentile, a fact that seemed almost surreal to me after all the years spent on construction sites, where I had come to doubt my abilities. I had always known I was capable, but the confirmation on that paper–the validation of my potential–was overwhelming.

I could not wait to share the news with Mr. Carter. He had been the first to see my potential, the one who had given me the chance I thought I would never have. When I showed him my results, his face lit up with a wide smile, and I could see the pride in his eyes. He clapped me on the back, congratulating me.

“I knew you had it in you,” he said warmly, his voice thick with emotion. “This is just the beginning. You are going to go far, mark my words.” His belief in me had been the driving force behind my determination and knowing that I had made him proud filled me with a sense of accomplishment that went beyond the grades themselves. He had changed my life, and now, I was on the path to fulfilling the dreams I had put on hold for so long.

Of course, the first people I called were my parents. When I told them the news–that I had aced the A-level exams–the silence on the other end of the line was palpable. My mother’s voice broke first, shaky with emotion. “Son, we are so proud of you,” she whispered. “You have made us so proud.”

I could hear my father in the background, his voice rough with tears of joy, and then my siblings were clamouring for the phone, each of them expressing their excitement and pride. My younger siblings, especially, were in awe–they had always seen me as the strong, hardworking eldest brother who did whatever it took to support the family. Now, I was someone they looked up to not only for my hard work but for my achievements.

“You did it, brother!” my youngest sister exclaimed, her voice bursting with excitement. “You are going to university! And you have been sending us to school, too. We are all so proud of you!” Hearing their pride, knowing how much this meant to them, was more valuable to me than any recognition.

They had watched me struggle and sacrifice for them, and now they were witnessing the result of all those efforts. My parents, who had once despaired at the loss of our land and livelihood, could now hold their heads high, knowing that their son had fought his way to a future that no one had thought possible.

As I stood on the brink of a new chapter in my life, I carried their pride with me. Mr. Carter, my parents, my siblings–they had all been part of this journey, and their belief in me had been the cornerstone of my success. I was not just doing this for myself, but for them. Their joy and pride became my fuel, propelling me forward as I prepared to enter university.

I applied to three universities in the country, hoping that one of them would offer me a chance. I had no idea what would happen, but I hoped for the best. To my astonishment, not only did all three universities accept me, but each of them offered me a prestigious, fully funded scholarship.

The scholarships covered everything–tuition, accommodation, books, and even a generous monthly allowance. The offer came with a single condition: I had to maintain a first-class CGPA. If my grades slipped outside the first-class range for two consecutive semesters, I would lose the scholarship.

It was an incredible opportunity; one I could not have imagined six years ago when I first stepped off the plane into this foreign land. This scholarship was not just an offer–it was a lifeline. It was funded by the country's government, given only to the most promising students, and it came with the expectation of excellence. It was a challenge I was more than willing to meet.

I knew the road ahead would not be easy, especially with the scholarship's condition that I had to maintain a first-class CGPA. But knowing that Mr. Carter, my family, and my siblings were rooting for me made the pressure easier to bear. I had come this far because of them, and I would continue to strive–not just for my own future, but for theirs as well.

When the time came to choose a university and a field of study, I knew exactly what I wanted. I chose the University of Solterra. My years working as a labourer had shown me the importance of materials–the strength and durability of concrete, steel, and other building elements. I had spent countless hours hauling them, seeing their flaws and strengths first hand.

This experience fuelled a new passion in me: I wanted to study Material Science and Engineering. I wanted to understand the materials that shaped the world I had worked in, to push the boundaries of what was possible in construction and technology.

The scholarship provided me with a monthly allowance that was twice the amount I had earned as a labourer, and with that, I was able to continue supporting my family back in Pamsia. I never stopped sending money home–only now, I could send even more.

My siblings were able to continue their education without interruption, my parents were relieved of their financial burdens, and I was even able to fully repay the debts that had accumulated over the years. Our family, once on the brink of despair, now had a brighter future.

As I walked onto campus for the first time, I felt a sense of awe. The grand buildings, the lush green lawns, the halls filled with eager students–it was a world I had dreamt of, but one I had never thought I would see. Yet, here I was, standing among them, ready to prove that I belonged. The pressure was immense, but it was nothing compared to what I had endured.

With every lecture, every lab session, I poured my heart into my studies, driven by the same motivation that had kept me going through the darkest times. I knew that slipping from a first-class position even once could jeopardise everything, but I was determined to make the most of this opportunity. I had spent too many years with my dreams on hold, and now, I was ready to chase them with everything I had.

This was only the beginning. The journey had been long and hard, but I had made it this far. And with each step forward, I knew I was closer to building not just a future for myself, but a better life for my family.

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University life was as intense as it was rewarding. Material Science and Engineering fascinated me from the start. The field bridged my past experiences with my future ambitions. As I learnt about materials–how they were structured, how they interacted with their environment, and how they could be manipulated to solve real-world problems–I began to connect this knowledge to my work on construction sites. I had spent years in buildings, inhaling dust, fumes, and various air pollutants, all the while wondering how these things affected the air we breathe.

It was during a lecture on building materials and their environmental impact that I found my passion for IAQ. The professor had discussed how poorly ventilated buildings, combined with certain construction materials, could create environments filled with harmful pollutants.

This struck a chord deep within me, as I remembered my long hours on those construction sites, often feeling the effects of poor air quality. I knew that people, especially in low-income areas like my home country of Pamsia, were exposed to these indoor pollutants daily, with little awareness of the long-term health risks.

As I delved deeper into my coursework, I realised that Material Science held the key to improving indoor environments. The properties of materials could be engineered to minimise the release of volatile organic compounds (VOCs), reduce particulate matter, and even purify air through innovative designs.

I began to focus my research on how material choices in building design could influence air quality, particularly in enclosed spaces where people spent most of their time. By the time I reached my third year, I had developed a clear vision: I wanted to use my knowledge of Material Science to reduce exposure to indoor air pollutants and improve public health.

My newfound passion fuelled me through the remaining months of my four-year Bachelor of Engineering undergraduate studies. I conducted independent research projects, working closely with my undergraduate dissertation professor to explore the intersection of materials science and engineering and environmental health.

I became particularly interested in the ways materials like gypsum, insulation, and certain types of paint could either trap pollutants or release harmful chemicals into the air over time. My focus was not just on theory but on real-world applications–how we could design better, healthier buildings for people everywhere, especially in places like Pamsia.

I graduated with a first-class degree, achieving a CGPA of 4.81 out of 5. I was named the best graduating student in my department, and to my surprise, I was the second-best graduating student in the entire Faculty of Engineering.

As I walked across the stage to receive my award, I could not help but think of all the people who had supported me along the way–my parents, my siblings, Mr. Carter. They had all believed in me when the future seemed bleak, and now, here I was, with the future wide open before me.

The recognition did not stop at graduation. Because of my academic excellence and research contributions, I was offered a lucrative PhD scholarship in the same department, focusing on Indoor Environmental Quality and Building Materials.

The scholarship would cover my tuition, provide for my accommodation, and give me a generous monthly stipend–more than enough to continue supporting my family back home, whose financial worries had long since eased thanks to the funds I had been sending during my undergraduate studies.

I accepted the offer without hesitation. This was the next step in my journey–a chance to delve deeper into the subject that had captured my heart and mind. My goal was clear: I would continue to explore how Material Science could transform indoor environments, making them safer and healthier for everyone, especially in developing countries where such improvements could have life-changing impacts. The PhD programme would not only deepen my expertise but also position me as a leader in this emerging field.

As I embarked on my PhD journey, I knew that the road ahead would be challenging. But I had faced challenges all my life, and I had never let them stop me. I had come too far to turn back now. Specifically, I wanted to use my PhD research study to explore how I could use my expertise in material science and engineering and the knowledge I had gained during my undergraduate studies and self-learning to address the problem of limited access to air cleaning systems in low-income countries.

In the first year of my PhD, I was determined to maintain the academic excellence that had brought me this far. The programme required me to complete six advanced modules within two semesters. Despite the demanding workload, I embraced each subject with passion, immersing myself in topics ranging from advanced material characterisation to environmental engineering principles.

Every moment outside the classroom was spent in the lab or the library, ensuring I had a deep understanding of each module's content. By the end of the year, my efforts paid off. I received A+ in three modules, A in two, and A- in one–solidifying my standing as one of the top students in the programme.

However, excelling in the modules was only the beginning. To advance from PhD student to PhD candidate, I had to pass both the written and oral qualifying examinations. The written exam tested my theoretical knowledge and research methodologies, while the oral exam required me to defend my research proposal in front of a panel of professors.

Drawing on my background in material science and engineering and my focus on IAQ, I presented a detailed research plan, confidently answering every question posed. Below are extracts from my oral presentation.

"Air cleaning systems, including air filters, purifiers, and other healthy air cleaning systems, are vital in indoor environments where air pollutants of both indoor and outdoor origins accumulate. Indoor sources such as household products, cooking emissions, mould spores, and pet dander contribute to compromised IAQ.

Additionally, outdoor pollutants like nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and particulate matter infiltrate indoors from urban traffic, industrial emissions, and construction activities.

Air cleaning systems play a critical role in removing or neutralising indoor air pollutants, which not only protects general health but is particularly crucial for vulnerable populations such as children, the elderly, and those with respiratory conditions.

Furthermore, research shows that poor IAQ impairs cognitive function and productivity. Air cleaning systems maintain healthier indoor environments, enhancing physical well-being and mental acuity, reinforcing their necessity in modern living and workplaces.

Air cleaning systems are rightfully recommended by IAQ experts to reduce occupants' exposure to pollutants from both indoor and outdoor sources. In high-income countries, access to these systems is generally feasible. However, the situation is vastly different in low-income countries, where financial limitations are significant.

Many people live on less than $2 a day, and many employed individuals often earn less than $50 a month. Purchasing and maintaining air cleaning systems is therefore unaffordable for the majority of the population. Thus, they are unable to benefit from air cleaning systems, leaving them vulnerable to air pollutants.

High outdoor air pollution from vehicular emissions and light generators worsens IAQ. Prolonged air pollutant residence time enhances indoor air chemistry; the use of candles and kerosene lanterns due to frequent and prolonged power outages, indoor cooking, and other indoor activities further degrades IAQ and extends exposure to air pollutants.

Prolonged exposure, combined with the lack of access to air cleaning systems, significantly increases the risk of poor health, particularly in residential settings. This predicament motivates my research, which aims to address these critical issues and find solutions for improving IAQ and health outcomes in vulnerable populations…….

…. The overarching research questions for my PhD research were: (i) How does the absence or limitation of air cleaning systems impact indoor air quality in low-income regions, and what specific health risks do occupants in these indoor environments face as a result? (ii) What are the technological, financial, and infrastructural barriers to the adoption of air cleaning systems in low-income countries, and how can strategic solutions be developed to improve their affordability, accessibility, and effectiveness? (iii) How effective, durable, and usable is the developed nature-inspired boxed air filter, costing less than 50 cents, in real-world residential indoor environments, and what impact does it have on reducing exposure to indoor air pollutants of interest and associated health risks?

These research questions informed the objectives for my PhD research. The objectives were: (i) To investigate the impact of limited or absent air cleaning systems on indoor air quality in low-income regions and assess the specific health risks faced by occupants in these indoor environments. (ii) To analyse the technological, financial, and infrastructural barriers to the adoption of air cleaning systems in low-income countries and develop strategic solutions to enhance their affordability, accessibility, and effectiveness. (iii) To evaluate the effectiveness, durability, and usability of the developed nature-inspired boxed air filter that costs less than 50 cents in real-world residential indoor environments, assessing its impact on reducing exposure to indoor air pollutants of interest and associated health risks…….”

Both exams went better than I could have hoped. Passing with distinction, I was officially recognised as a PhD candidate, bringing me one step closer to completing the journey I had embarked on 18 months earlier. I spent an additional two years and six months conducting my main research study in Pamsia, a low-income and tropical country, and writing my PhD thesis.

With the research grant, generous support of local researchers and ministries in Pamsia, and the moral support of my aged parents and siblings, I led the field study in my capacity as a PhD researcher under the supervision of my PhD supervisor, Professor Evelyn Mohan. Below, I provide summaries of my PhD research methods and results that addressed my research questions and objectives.

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Research Methods:

Research Objective 1: Exposure Risk Assessment

–I*ndoor Air Quality Condition*—

The selection of sampling locations in this study was pivotal due to its impact on the overall representativeness of the findings concerning IAQ in various socio-economic settings. Conducted in a low-income country, the study had to account for the diverse environmental and socio-economic conditions that significantly influenced IAQ. The choice of this location was informed by the socio-economic status of the area, its environmental vulnerabilities, and the health challenges related to poor IAQ.

The region’s lack of widespread air cleaning systems and the prevalence of building materials that did not promote optimal ventilation further justified its selection. By focusing on such a region, the study aimed to highlight disparities in IAQ across different socio-economic environments and to explore feasible interventions that could mitigate the health risks associated with poor IAQ.

The research focused on naturally ventilated residential buildings in Pamsia. The study aimed for a balanced geographical distribution, including urban, suburban, and rural areas, to ensure a representative sample of different living conditions.

Urban areas, which typically experience higher levels of both indoor and outdoor air pollutants, were prioritised, comprising 40% of the sampling sites. This focus on urban environments was crucial due to their generally more severe air quality issues, stemming from dense traffic, industrial activities, and higher population density.

Suburban areas, making up 30% of the sampling sites, generally have moderate pollution levels and somewhat better infrastructure compared to rural areas. Rural areas, also representing 30% of the sites, were included to examine how lower pollution levels and the lack of infrastructure impacted IAQ. Rural buildings often suffer from poor construction quality.

To reflect economic realities, the study reduced the number of households with air cleaning systems to 15 out of 120 locations. This reduction mirrored the limited access to such technologies in low-income settings. The majority of the selected sites did not have air cleaning systems, which is typical for low-income countries.

The 15 locations with air cleaning systems were predominantly situated in wealthier urban areas where residents had a mixture of naturally ventilated scenarios and use of split air-conditioning system with in-built air cleaning system or self-alone air cleaning system. This distribution enabled a comparison between households with and without air cleaning technologies, highlighting disparities in air quality and health risks across different socio-economic groups.

Central to the study was the continuous monitoring of IAQ across the selected locations, focusing on air pollutants with known health impacts. The key air pollutants monitored included particulate matter ($PM_{2.5}$ and PM_{10}), volatile organic compounds (VOCs), carbon monoxide (CO), and carbon dioxide (CO_2). These air pollutants were chosen due to their significant health risks, especially in environments where outdoor pollution, indoor combustion (such as cooking), and poor ventilation can lead to severe health issues.

High-precision air quality monitoring devices were used for continuous data collection over a six-month period. These devices were portable and calibrated to measure air pollutants at regular hourly intervals. They were capable of detecting both low and high concentrations of $PM_{2.5}$ and PM_{10}, VOCs, CO, and CO_2, ensuring that the data accurately reflected varying pollution levels in different environments.

The monitoring period lasted six months to capture changes in IAQ due to seasonal variations, external pollution sources, and occupant activities. Devices were installed at 1.5 metres above the ground to mirror the breathing zone of occupants.

In homes, the devices were placed in living rooms; in schools, they were situated in classrooms; and in workplaces, they were set up in general working areas. This consistent placement ensured that the data was representative of the environments where people spent the most time.

The remaining 105 locations, which lacked air filtration or purification systems, represented typical households in low-income settings. That is, these residential indoor environments were 100% naturally ventilated but form of air cleaning system in place. Comparing these groups allowed for an assessment of the impact of air cleaning systems on indoor air pollutants and the potential health benefits.

To account for the influence of outdoor pollution on indoor air quality, simultaneous monitoring of outdoor air was conducted at each location. Monitoring stations were installed near the sampling sites to track ambient levels of $PM_{2.5}$, PM_{10}, VOCs, CO, and CO_2. These outdoor measurements enabled the calculation of indoor-to-outdoor (I/O) ratios for each location, providing insights into the sources of indoor air pollutants and the effectiveness of different buildings in preventing the infiltration of outdoor air pollutants.

—*Health Risk Assessment*—

The health risk assessment aimed to explore the relationship between IAQ and the health outcomes of occupants. With the prevalence of respiratory and cardiovascular diseases in areas with poor air quality, the study focused on these health risks by gathering data on symptoms and diagnosed conditions related to air pollution.

Health data were collected using a combination of medical records and detailed surveys completed by occupants. The surveys included questions about respiratory symptoms such as coughing, shortness of breath, and wheezing, as well as cardiovascular conditions like hypertension and chest pain.

Information about pre-existing conditions, such as asthma or chronic obstructive pulmonary disease (COPD), was also gathered. Additionally, demographic data, such as age, sex, occupation, and smoking status, were collected to control for variables that could influence health outcomes.

The study employed a cross-sectional design to assess the correlation between IAQ and health outcomes at a single point in time. This design provided a snapshot of the potential health impacts of exposure to poor IAQ, allowing for analysis of health risks associated with different indoor environments.

Occupants were stratified into different risk categories based on their exposure to indoor air pollutants and pre-existing health conditions. This stratification focused on vulnerable populations, such as children, the elderly, and individuals with pre-existing respiratory or cardiovascular conditions. The goal was to quantify the increased risk of illness due to poor IAQ and to identify which groups were most affected by indoor air pollutants.

—*Data Analysis*—

The final phase of the study involved a thorough statistical analysis of the IAQ and health data to explore the relationship between indoor air pollutants and health risks. Regression models were used to estimate the association between indoor air pollutant concentrations and health outcomes.

Multiple linear regression was applied for continuous outcomes, such as lung function and blood pressure, while logistic regression was used for binary outcomes, such as asthma diagnoses. The models adjusted for confounding variables, including age, smoking status, socio-economic status, and outdoor air pollution levels.

The indoor-to-outdoor (I/O) ratio was calculated for each air pollutant at each location to determine how much indoor air pollutants were influenced by outdoor sources. Comparing I/O ratios across locations with and without air cleaning systems provided insights into the effectiveness of air cleaning technologies in reducing indoor air pollutants.

Sensitivity analyses were conducted to ensure the robustness of the findings. These analyses included varying assumptions about the health risks associated with specific air pollutants and adjusting for different exposure periods. Alternative statistical models were also tested to account for clustering within geographical regions or building types, further enhancing the credibility of the study's conclusions.

Research Objective 2: Filter adoption barriers

—Economic and Infrastructure Challenges—

The initial phase of the study involved conducting surveys and focus groups to identify the specific technological, financial, and infrastructural challenges encountered by low-income populations in relation to IAQ. This phase was crucial for understanding the context and constraints that affected the adoption of air-cleaning systems in resource-limited settings.

Surveys were designed to collect quantitative data on a range of issues, including the current state of IAQ, the prevalence of respiratory and cardiovascular health problems, and the general awareness of air pollution among low-income households.

The survey instruments included a mix of closed and open-ended questions to capture both quantitative metrics and qualitative insights. The sampling frame for the surveys encompassed a representative cross-section of low-income households, schools, and workplaces, ensuring a comprehensive understanding of the environmental and socio-economic factors influencing IAQ.

Focus groups were employed to gather in-depth qualitative data. These discussions included diverse groups of stakeholders such as community members, local health workers, and leaders of non-governmental organisations (NGOs).

Focus group discussions were structured to explore participants' perceptions of IAQ issues, barriers to adopting air-cleaning technologies, and potential solutions. The insights from these discussions provided valuable context for understanding the survey data and helped to refine the focus of subsequent research phases.

—Technological Feasibility Study—

The technological feasibility study aimed to develop a durable, efficient, easy-to-maintain, and nature-inspired air filter box priced below $0.50, specifically designed to address the financial and environmental constraints faced by low-income communities, particularly those living on less than $2 per day.

The primary objective was to create a solution that aligned with local conditions and available resources, drawing inspiration from natural processes to ensure its effectiveness and affordability.

The research commenced with an extensive review of natural biofiltration mechanisms, with a focus on phytoremediation. Phytoremediation is the process by which plants absorb and neutralise air pollutants from the air and soil.

This foundational understanding guided the application of biomimicry principles in designing the air filter box. The aim was to develop a low-cost, passive air filter that does not rely on electricity or complex mechanical components, making it suitable for resource-limited settings.

Identifying locally available materials to emulate these natural biofiltration mechanisms was a crucial aspect of the study. The research highlighted plants with known air-purifying properties, such as spider plants (Chlorophytum comosum) and peace lilies (Spathiphyllum spp.), which effectively absorb air pollutants like volatile organic compounds (VOCs), carbon dioxide (CO2), and particulate matter (PM).

Additionally, biochar–a charcoal-like substance produced from organic materials through pyrolysis–was selected for its high adsorption capacity and low production cost. Biochar's accessibility in rural areas and its inexpensive production method were essential for keeping the cost of the air filter box below the $0.50 target.

Several prototypes of the air filter box were developed using these natural and locally sourced materials. The design emphasised modularity to ensure ease of assembly, maintenance, and repair. This approach was intended to facilitate integration into homes and community buildings, even in areas with limited infrastructure.

The prototypes were then tested in laboratory settings that simulated indoor environments with high levels of air pollutants. Key air pollutants, including particulate matter ($PM_{2.5}$ and PM_{10}), volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and carbon dioxide were assessed, given their prevalence in low-income areas due to biomass use for cooking and heating. The performance of the prototypes was evaluated to determine their effectiveness in reducing these air pollutants while ensuring long-term durability and functionality.

The study aimed to validate that the nature-inspired air filter box could deliver significant improvements in IAQ at an affordable cost, providing a sustainable solution tailored to the needs of the target population.

—Financial Modelling—

The financial modelling focused on developing a solution that would make the nature-inspired air-cleaning system available for less than 50 cents, addressing the reality that households earning less than $2 per day face numerous competing financial priorities. The goal was to ensure that even the most economically disadvantaged populations could afford and benefit from the system, without requiring any form of external financial aid, loans, or unsustainable financial burdens.

To achieve this, the financial strategy centred on significantly reducing production and distribution costs. This involved leveraging partnerships with governments, non-governmental organisations (NGOs), and international agencies to provide the necessary support to offset the manufacturing and transportation costs.

These entities played a pivotal role in offering direct subsidies that allowed the system to be priced below 50 cents. The use of subsidies ensured that the air-cleaning systems were affordable even to those with the most limited financial resources, without compromising on the system's durability or effectiveness.

In parallel, local community-driven initiatives were employed to further drive down costs. These included using locally sourced materials and decentralising production to local manufacturers, which not only reduced transportation and logistical expenses but also stimulated local economies. Collective purchasing through community groups was also explored, allowing households to buy in bulk at reduced rates, thus maintaining affordability.

The technological feasibility study for the nature-inspired air-cleaning system, priced under $0.50, included comprehensive cost-benefit analyses to evaluate its economic viability and value delivery. This analysis aimed to determine the system's effectiveness in reducing indoor air pollutants and its subsequent impact on public health and economic costs.

The core of the evaluation was the benefit-to-invested-cost ratio, which assessed both immediate and long-term benefits. Immediate benefits included improvements in air quality and reductions in air pollutant exposure. Long-term advantages were quantified in terms of potential healthcare cost savings, enhanced productivity, and improved quality of life.

Research Objective 3: Nature Inspired Filter Effectiveness Assessment

—Exposure Control—

This pilot study was conducted to evaluate the effectiveness, durability, usability, and health impact of a nature-inspired air filter box costing less than $0.50 in low-income residential environments. These households, selected from rural and peri-urban areas, typically relied on biomass fuels for cooking and heating, leading to significant indoor air pollutants.

The study aimed to assess whether these low-cost air filter boxes could reduce exposure to air pollutants such as particulate matter ($PM_{2.5}$, PM_{10}), volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and carbon dioxide (CO_2), and improve respiratory health outcomes.

A total of 100 households were randomly assigned to either the intervention group, where air filter boxes were installed, or the control group, where no filters were used. Both groups consisted of 50 households each. This randomised controlled trial design allowed for comparative analysis of indoor air pollutant levels and health impacts between households using the filters and those without them.

The intervention households received air filters designed to be easy to maintain and integrate into daily life without the need for complex upkeep or technological expertise. These 100 households were part of the naturally ventilated 105 households with no air cleaning systems in the exposure risk assessment done for objective 1 fulfilment.

The study included comprehensive IAQ monitoring to measure the effectiveness of the air filter boxes in reducing indoor air pollutants. Continuous IAQ monitors were installed in both the living areas and kitchens of all households in the study, capturing data on $PM_{2.5}$, PM_{10}, VOCs, CO, NO_2, SO_2, and CO_2 at 15-minute intervals. These air pollutants were selected based on their known health risks and prevalence in households that use biomass fuels.

The monitoring period continued for six months post-installation, ensuring that any reductions in indoor air pollutant concentrations could be tracked over time and under varying environmental conditions, such as seasonal changes. This allowed for the capture of both short-term and long-term effects of the air filters on IAQ.

Data were collected using both real-time continuous monitors and passive samplers. The passive samplers provided an additional layer of data, which was later analysed in a laboratory setting. The continuous monitors transmitted data to a central database for real-time analysis, while site visits were conducted by the research team every month to ensure data quality and check the functioning of the devices.

Control households, where no filters were installed, were monitored concurrently, providing a robust comparative dataset. This allowed the study to isolate the effect of the air filters from other factors that might influence IAQ, such as weather or cooking patterns.

—Durability and Usability Evaluation—

Alongside IAQ monitoring, the durability and usability of the air filter boxes were evaluated. Durability was assessed by tracking the physical integrity of the filter boxes over the six-month study period. During monthly site visits, researchers inspected the filters for signs of wear and tear, documented any necessary repairs or replacements, and recorded how often users performed maintenance tasks such as cleaning the filter surface or replacing biochar. Minimal maintenance was expected to ensure that the filter boxes remained practical for long-term use in low-income households.

Usability was evaluated through both direct observation and participant feedback. Researchers observed how easily participants could integrate the air filters into their daily routines, such as whether they could install the filters themselves, perform basic maintenance, and operate the filters without any technical difficulties.

User satisfaction was measured through surveys administered at the beginning, middle, and end of the study. These surveys asked participants about the ease of installation, maintenance requirements, perceived improvements in IAQ, and any challenges they encountered.

At the conclusion of the study, focus group discussions were conducted with participants from the intervention group to gather more detailed feedback on the usability of the air filters. These discussions provided insights into how well the filters fit into the households' daily lives and whether participants would be willing to continue using the filters in the future. The usability data were crucial for understanding the practical challenges and potential for widespread adoption of the filters.

—*Health Impact Assessment*—

To evaluate the health benefits of the air filter boxes, the study tracked respiratory and cardiovascular symptoms among household occupants, focusing on vulnerable populations such as children, the elderly, and individuals with pre-existing health conditions.

Baseline health data were collected through structured health surveys administered at the start of the study. These surveys focused on symptoms commonly associated with indoor air pollutants, such as coughing, wheezing, shortness of breath, eye irritation, headaches, and cardiovascular issues.

Follow-up health surveys were conducted every two months throughout the six-month study period to monitor changes in these symptoms. In cases where participants reported significant health changes, additional medical examinations were conducted to obtain objective health data, including lung function tests and measurements of blood oxygen levels.

Health outcomes in the intervention group were compared with those in the control group to determine whether reductions in indoor air pollutants concentrations led to measurable improvements in respiratory and cardiovascular health. Statistical analyses were used to evaluate the correlation between reduced exposure to indoor air pollutants (as measured by the IAQ monitors) and changes in the frequency and severity of health symptoms.

The study also aimed to estimate the potential long-term health benefits of using the air filters, based on the observed improvements in IAQ and short-term health outcomes. Although the study duration was limited to six months, modelling techniques were employed to predict the potential cumulative health benefits of prolonged use of the filters over several years. This modelling took into account the reduction in indoor air pollutant exposure and the expected decrease in health risks associated with indoor air pollutants.

By correlating indoor air pollutant reduction with reported health improvements, the study provided a comprehensive analysis of how the air filter boxes affected the overall well-being of household occupants. This holistic approach allowed for an understanding of both the environmental and health impacts of the intervention.

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Research Findings

Research Objecti*ve 1: Exp*osure Risk Assessment

—*Indoor Air Quality Condition*—

Significant differences in IAQ were observed between low-income and wealthier households. In low-income urban settings, where air cleaning systems were largely absent, indoor air pollutant concentrations were notably higher. The average concentration of particulate matter (PM2.5) in these households was 22.5 µg/m³, exceeding the World Health Organization (WHO) guideline of 15 µg/m³ by 50%.

This elevated level of PM2.5 was accompanied by high concentrations of volatile organic compounds (VOCs), carbon monoxide (CO), and carbon dioxide (CO2), exacerbated by both the infiltration of outdoor air pollutants and indoor sources such as cooking with open stoves. CO2 concentrations in these households averaged 1,200 ppm, surpassing the recommended IAQ standard of 1,000 ppm, indicating poor ventilation and insufficient fresh air circulation.

Wealthier households, typically equipped with modern air cleaning systems such as HEPA filters, exhibited significantly better IAQ. The average $PM_{2.5}$ concentration in these homes ranged between 8 and 10 µg/m³, well below the WHO threshold. VOC levels were also reduced, averaging below 400 µg/m³, CO levels remained within safe limits, and CO_2 concentrations averaged 800 ppm, reflecting better ventilation and air filtration.

This stark contrast highlights the impact of socio-economic status on access to technologies that mitigate indoor air pollutants, emphasising the health disparities faced by lower-income populations who lack such protections.

Ventilation emerged as a critical factor influencing IAQ across different types of homes. The study found that 65% of the sampled homes had poor ventilation, which led to higher concentrations of indoor air pollutants.

Poorly ventilated homes had PM10 concentrations 1.8 times higher than those with adequate ventilation. Similarly, VOC levels in poorly ventilated homes averaged 700 µg/m³, compared to 300 µg/m³ in well-ventilated homes. CO_2 levels in poorly ventilated homes were also notably higher, averaging 1,300 ppm, compared to 700 ppm in homes with proper ventilation.

These findings underscore the role of ventilation, especially when supported with air cleaning system in location with poor outdoor air quality, in controlling indoor air pollutant concentrations, with inadequate airflow exacerbating pollutant accumulation, particularly in homes where external air exchange is limited.

The calculation of indoor-to-outdoor (I/O) ratios provided valuable insights into the extent of outdoor air pollutant infiltration into indoor environments. In urban areas, where outdoor air pollution was severe, the average I/O ratio for $PM_{2.5}$ was 0.85, indicating a strong correlation between outdoor and indoor air quality. CO_2 levels followed a similar trend, with I/O ratios averaging 0.9 in urban settings, reflecting the combined effect of outdoor pollution infiltration and indoor occupant activities.

This suggests that outdoor air pollutants were a significant contributor to indoor air quality issues. In contrast, suburban and rural areas exhibited lower I/O ratios, with averages of 0.6 for $PM_{2.5}$ and 0.5 for VOCs. This indicates that indoor sources of air pollution, such as combustion for cooking, played a more significant role in these areas.

In poorly ventilated rural homes, the I/O ratio for CO often exceeded 1.0, revealing that indoor air pollution sources predominated over outdoor air pollution, while CO_2 levels remained high due to inadequate ventilation, with I/O ratios averaging 1.1.

—Health Effects—

In households without air cleaning systems, the negative impact on respiratory health was profound in naturally ventilated buildings located in a tropical environment. Among the 105 households without any form of air cleaning, residents were exposed to elevated concentrations of indoor air pollutants such as particulate matter ($PM_{2.5}$), carbon monoxide (CO), and carbon dioxide (CO_2). The absence of filtration and the accumulation of these harmful substances contributed to significantly higher rates of respiratory conditions.

Chronic coughing, shortness of breath, and wheezing were commonly reported, with symptoms particularly severe in homes where cooking with biomass fuels, such as wood or coal, was prevalent. These fuels emitted hazardous air pollutants, including fine particulate matter, which accumulated indoors due to poor ventilation.

In homes where $PM_{2.5}$ levels exceeded 22.5 μg/m³, the study observed a 35% increase in chronic coughing and a 40% rise in wheezing among residents. Additionally, CO_2 levels consistently reached 1,200 ppm in households with high occupancy rates and poor ventilation, further contributing to discomfort and respiratory distress.

Children in these households were especially vulnerable. The combination of poor ventilation and the lack of air cleaning systems created environments where air pollutants lingered for extended periods, triggering respiratory infections and asthma attacks.

Asthma exacerbations increased by 45%, leading to a notable rise in emergency hospital visits for affected children. In instances, where windows were often kept closed to prevent outdoor heat or pollutants from entering, the resulting trapped indoor air pollutants further compromised respiratory health.

In addition to respiratory issues, cardiovascular health was negatively impacted in these households. Elderly residents were particularly susceptible, with a marked increase in chest pain and hypertension due to long-term exposure to particulate matter, CO, and elevated CO_2 concentrations.

In homes where PM_{10} levels consistently surpassed 100 μg/m³, chest pain incidents increased by 25%, and cases of high blood pressure were 30% more frequent. This chronic exposure, combined with indoor CO_2 concentrations often exceeding 1,500 ppm, heightened the risk of cardiovascular complications, especially in elderly individuals.

Conversely, the 15 households that utilised air cleaning systems showed notable health improvements. Respiratory symptoms such as coughing and wheezing was about 60%, and cardiovascular complaints like chest pain and hypertension was about 40% lower than those reported in 105 households.

Families in these homes reported a lesser medical visits and hospitalisations, particularly among children with asthma and elderly residents with pre-existing heart conditions. This underscores the potential benefits of air cleaning measures in mitigating the harmful effects of indoor air pollutants.

For residents with pre-existing conditions, such as chronic obstructive pulmonary disease (COPD) and heart disease, the absence of air cleaning systems significantly worsened their health outcomes. In homes without filtration, COPD flare-ups increased by 50%, with residents frequently requiring medical attention.

Similarly, individuals with cardiovascular diseases experienced irregular heartbeats and spikes in blood pressure due to the unchecked levels of indoor air pollutants, combined with elevated CO2 levels. The lack of proper ventilation exacerbated these issues, trapping pollutants inside and posing serious risks to those with chronic health conditions.

R*esearch Objective 2: Filter Adoption B*arriers

—*Economic and Infrastructure Challenges*—

The findings from the surveys and focus groups highlighted the significant challenges that low-income populations face in addressing indoor air quality. The survey data revealed that the majority of households in the study experienced poor air quality, with a high concentration of air pollutants such as $PM_{2.5}$ and carbon monoxide (CO).

The widespread use of biomass fuels for cooking and heating in these communities was a major contributor to indoor air pollutants, and most households lacked adequate ventilation systems. Open windows were commonly used as the primary means of air circulation, but this proved insufficient in mitigating the pollution from both outdoor and indoor sources.

The economic limitations faced by these households were a critical factor impeding the adoption of air-cleaning technologies. Most households spent a minimal amount on utilities, and the prospect of investing in air-cleaning solutions was perceived as unaffordable.

The survey findings underscored the financial strain on these communities, making it clear that any proposed air-cleaning technology would need to be highly cost-effective and low-maintenance to be considered viable. Furthermore, the survey indicated limited awareness of affordable and accessible options to improve indoor air quality, with many participants expressing uncertainty about how to tackle the issue effectively.

Focus group discussions provided deeper insights into these challenges, reinforcing the findings from the survey. Participants cited the high cost of air-cleaning systems as one of the primary reasons for not adopting such technologies. Even relatively inexpensive options were out of reach for families already struggling to cover basic necessities such as food, shelter, and clothing.

Many participants expressed frustration with the lack of support from both the government and private sectors in providing solutions to their air quality problems, further diminishing their confidence in adopting new technologies.

Infrastructural challenges were also a recurring theme in the focus groups. Many participants pointed out that unreliable electricity, combined with overcrowded living conditions, exacerbated air quality issues in their homes.

The lack of proper ventilation systems, poorly constructed housing, and minimal insulation made it difficult to keep indoor spaces free from outdoor air pollutants, particularly in densely populated urban areas. These environmental conditions worsened indoor air quality and rendered many air-cleaning solutions impractical, especially those requiring a stable energy source.

A sense of resignation about the poor air quality in their communities was also apparent. Participants described air pollution as an external problem, beyond their control, with little hope of intervention from outside sources.

Many viewed air-cleaning technologies as irrelevant to their day-to-day survival, prioritising immediate economic concerns over long-term health benefits. These discussions revealed the need for a technology that was not only affordable but also tailored to the specific environmental and socio-economic conditions faced by these communities.

—*Technological Feasibility Study*—

The technological feasibility study of the air filter box revealed a highly effective and practical solution specifically tailored for low-income households. The air-cleaning system was developed to meet a target cost of below $0.50, utilising biomimicry principles and local resources to address air pollution challenges efficiently. The design effectively balanced affordability and functionality, making it suitable for environments where traditional active systems might be financially inaccessible.

The air filter box was compact, measuring approximately 30 cm in height, 20 cm in width, and 10 cm in depth. The construction was designed for ease of use, allowing for straightforward assembly and disassembly with minimal tools or technical knowledge. The exterior was made from recycled cardboard or other locally sourced, inexpensive materials, ensuring low production costs while maintaining structural durability. The modular design allowed household members to easily repair, clean, or replace components, enhancing the filter's longevity.

The filtering system inside the box combined natural materials with an efficient, low-cost fan system. The bottom layer featured biochar, a charcoal-like substance produced from organic waste through pyrolysis.

Biochar's porous structure is reported to efficiently adsorbed particulate matter such as $PM_{2.5}$ and PM_{10}, as well as gaseous pollutants including carbon monoxide (CO), volatile organic compounds (VOCs), and nitrogen dioxide (NO_2).

Its high surface area made it ideal for capturing a broad spectrum of pollutants. Biochar was both abundant and inexpensive to produce locally, which was crucial for maintaining the filter's cost below $0.50.

Above the biochar layer, the filter incorporated small pouches of air-purifying plants such as spider plants (Chlorophytum comosum) and peace lilies (Spathiphyllum spp.). These plants were chosen for their ability to absorb pollutants like formaldehyde and benzene from the air. Their ease of growth and availability in local markets made them a practical and sustainable choice for low-income households.

The air-purifying plants were housed in small, removable pouches. These pouches could be easily replaced or refreshed as the plants grew or became less effective. This design allowed users to maintain the filter's air-purifying capabilities with minimal effort.

The pouches were designed to be simple to handle, ensuring that users could manage plant care without requiring extensive gardening knowledge. That is, the design enables users to perform maintenance without special tools or technical expertise.

To enhance the effectiveness of the filter, a small solar-powered fan was integrated into the design. The fan was strategically placed to draw air through the filter media, improving air circulation and overall Clean Air Delivery Rate (CADR).

A compact, low-cost solar panel powered the fan, ensuring that the system remained operational without incurring ongoing electricity costs. The fan's design was optimised to be energy-efficient and cost-effective, using minimal solar panel surface area and inexpensive materials to ensure that the total cost remained below $0.50, especially with the potential large market size.

The air filter box utilised both natural and active mechanisms to improve air quality. Air entered the box through small openings along the bottom and sides. The solar-powered fan drew the polluted air through the biochar and plant layers, where pollutants were filtered out.

Clean air was then expelled through the top of the box, ensuring that the air circulated back into the room with significantly reduced pollutant concentrations. The integration of the fan provided an increased CADR compared to passive systems, enhancing the filter's effectiveness while maintaining cost efficiency.

The solar-powered fan was designed to be durable and low-maintenance. The fan's simplicity, coupled with the use of a cost-effective solar panel, ensured that maintenance requirements were minimal. The fan and solar panel were both designed for long-term use, reducing the need for frequent replacements or repairs.

The solar-powered fan system was designed to be both cost-effective and efficient. By utilising a compact solar panel and an energy-efficient fan, the design managed to keep production costs low while significantly enhancing the air filter's performance. The low-cost solar panel ensured that the filter remained affordable, even with the added fan component, achieving the target cost of below $0.50.

The design allowed for scalability and adaptability. For larger spaces or environments with higher pollution levels, multiple units could be deployed to increase the overall filtration capacity. The filter's modular nature meant that additional units could be added as needed to improve air quality across different areas of the home.

The air filter box, with its innovative use of biochar, air-purifying plants, and a solar-powered fan, provided a practical, cost-effective solution to indoor air pollution in low-income households. Its design addressed key challenges, including affordability, ease of maintenance, and effective air filtration, making it a highly adaptable option for resource-constrained communities.

The laboratory testing and evaluation of the air filter prototypes demonstrated their potential for effectively improving IAQ in low-income households. In controlled environments, the filters were tested for their ability to reduce concentrations of particulate matter ($PM_{2.5}$ and PM_{10}), volatile organic compounds (VOCs), carbon dioxide (CO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), and sulphur dioxide (SO_2), all of which are common pollutants from combustion sources.

In environments with high initial levels of $PM_{2.5}$, the filters successfully reduced concentrations by 45%, while PM_{10} concentrations were reduced by 50%. Carbon monoxide levels were also reduced by 30%, with notable effectiveness in kitchens where open-fire cooking methods were used. Nitrogen dioxide and sulphur dioxide concentrations saw moderate reductions of around 25% each, demonstrating the filter's capacity to address a broad range of pollutants commonly found in low-income homes.

VOCs concentrations were reduced by approximately 40%, showcasing the filter's ability to capture gaseous pollutants that originate from household products, building materials, and biomass fuels.

Carbon dioxide levels, which are indicative of ventilation effectiveness, were reduced by around 15%, bringing indoor CO_2 concentrations closer to recommended levels of 1,000 ppm or below. This reduction, while modest, highlighted the filter's supplementary role in improving air quality alongside natural ventilation practices in low-income settings.

The filters also performed well under conditions where access to electricity was limited or unreliable. Given the simplicity of the design, households would not need to rely on external power sources, addressing a major infrastructural concern identified in the survey and focus group phases.

The use of locally sourced biochar not only ensured that the filters could be produced at a low cost, but also supported the scalability of the technology for widespread use in resource-constrained environments.

Overall, the testing results indicated that the air filters could significantly reduce indoor air pollutant concentrations, offering a viable and cost-effective solution to improving air quality in low-income households. The modular and durable design of the filters, combined with the availability of locally sourced materials, made them a promising technology for addressing the air quality challenges identified in the earlier phases of the research.

—*Financial Modelling*—

The financial modelling for the nature-inspired air cleaning system successfully demonstrated that it could be produced and distributed for under 50 cents, aligning with the objective of making the system accessible to households earning less than $2 per day. Several key findings emerged from this study.

The involvement of governments, non-governmental organisations (NGOs), and international agencies was crucial in achieving the low cost. These entities provided essential subsidies that reduced the manufacturing and transportation costs of the air cleaning system.

This financial support ensured that the system could be priced below 50 cents, effectively reducing the financial burden on end-users and making it affordable for the most economically disadvantaged populations.

The use of locally sourced materials and decentralised production contributed significantly to cost reduction. By sourcing materials from local suppliers and decentralising production to local manufacturers, the system benefitted from lower transportation and logistical expenses. This approach not only reduced production costs but also supported local economies, making the air cleaning system more affordable.

Community-driven initiatives also played a role in further driving down costs. Bulk purchasing arrangements through community groups allowed households to buy the air cleaning systems at reduced rates. This collective purchasing strategy leveraged economies of scale, lowering the cost per unit and ensuring that the system remained within the 50 cents target.

The cost-benefit analysis revealed that the air cleaning system provided substantial benefits relative to its low cost. As evident from the laboratory study, immediate benefits included significant improvements in IAQ and reductions in pollutant exposure.

Long-term benefits, as evident from artificial intelligence supported simulation software were evidenced by notable healthcare cost savings and enhanced productivity. The strong benefit-to-cost ratio demonstrated that despite the minimal price, the system offered a considerable return on investment.

The analysis also highlighted the system's effectiveness in reducing healthcare costs associated with poor IAQ. The improvements in IAQ led to fewer health issues and lower healthcare expenditures, validating the economic viability of the system. Additionally, healthier individuals experienced increased productivity, contributing to the overall economic benefits of the system.

The scalability of the air cleaning system was confirmed, with the design and production model proving adaptable to various local contexts. The system could be effectively deployed across different regions, ensuring its wide implementation in economically constrained areas.

Overall, the financial modelling confirmed that the nature-inspired air cleaning system could be produced, distributed, and implemented for less than 50 cents. The system provided significant economic and health benefits, validating its role as a viable and practical solution for improving indoor air quality in resource-constrained environments.

Research Objective 3: Nature Inspired Filter Effectiveness Assessment

—Exposure Control—

The pilot study uncovered notable disparities between households equipped with nature-inspired air filters (intervention households) and those lacking any air cleaning systems (control households). Over a six-month monitoring period, intervention households demonstrated significant improvements in IAQ, primarily due to reductions in both indoor and outdoor air pollutants, while control households remained exposed to high levels of indoor air pollutants from both sources.

In intervention households, the average reduction in $PM_{2.5}$ concentrations was 45% across all monitored indoor environments, with the most pronounced improvement in kitchens where biomass fuel combustion–a significant source of indoor pollution–was frequent.

$PM_{2.5}$ particles, known for their ability to penetrate deep into the lungs, were efficiently captured by the filters, and this reduction was sustained over the study period. In contrast, $PM_{2.5}$ levels in control households remained unchanged, especially during peak cooking hours, with outdoor sources like vehicular emissions exacerbating IAQ.

For PM_{10}, intervention households saw a 38% reduction, while control households experienced consistent high concentrations due to outdoor contributions such as vehicular traffic, dust, and industrial emissions. The lack of filtration in these homes allowed coarse particulates to accumulate indoors, leading to frequent exceedances of recommended air quality levels.

The indoor-to-outdoor (I/O) ratios for both $PM_{2.5}$ and PM_{10} in intervention households were consistently below 1.0, indicating the filters' ability to reduce the amount of outdoor particulate matter entering the indoor environment. In control households, the I/O ratios were close to or above 1.0, showing significant infiltration of outdoor pollutants during high pollution periods such as rush hours.

Volatile organic compounds (VOCs), harmful gases often released from biomass combustion and household products, saw a 32% reduction in intervention households. The filters captured these pollutants effectively, particularly in kitchens where biomass fuel was commonly used. Control households, however, saw no reduction, and VOC concentrations either remained stable like objective 1 study or increased during cooking activities.

Carbon monoxide (CO) concentrations in intervention households experienced a 41% reduction, particularly during biomass fuel combustion for cooking. The filters effectively lowered CO concentrations, while in control households, CO concentrations remained high, frequently exceeding WHO guidelines during cooking times, posing significant health risks.

For carbon dioxide (CO_2), intervention households demonstrated a modest reduction of 18%. This reduction indicated improved ventilation efficiency, as the filters, though not primarily designed for CO_2 removal, supported the overall decrease in indoor air pollutant concentrations.

CO_2 is an important indicator of IAQ and ventilation effectiveness, and this reduction in intervention households brought indoor CO_2 concentrations closer to the recommended levels (around 1,000 ppm), particularly during cooking and periods of low ventilation. In control households, CO_2 levels either remained unchanged or increased, particularly in enclosed spaces with poor ventilation.

Nitrogen dioxide (NO_2) and sulphur dioxide (SO_2) saw reductions of 25% and 27%, respectively, in intervention households, particularly in areas where biomass combustion was frequent. Control households, on the other hand, experienced persistent high concentrations of these air pollutants, especially during cooking or periods of increased outdoor emissions from traffic or industrial activities.

Statistical analysis revealed that reductions in $PM_{2.5}$, PM_{10}, VOCs, CO, CO_2, NO_2, and SO_2 concentrations in intervention households were statistically significant ($p < 0.05$), confirming the efficacy of the nature-inspired filters in improving IAQ and reducing the infiltration of outdoor pollutants.

Conversely, control households, which lacked any form of air filtration, showed no significant improvements, underscoring the importance of these filters in protecting health and mitigating exposure to harmful air pollutants.

The substantial reductions in both particulate matter ($PM_{2.5}$ and PM_{10}) and gaseous pollutants (VOCs, CO, CO_2, NO_2, and SO_2) in intervention households demonstrated the filters' capacity to address both indoor and outdoor air pollution, offering a scalable and sustainable solution for improving IAQ in low-income environments.

—Durability and Usability Evaluation—

The durability of the nature-inspired air filter boxes was a pivotal aspect of the study, given their design, which incorporated cost-effective and locally sourced materials such as biochar and plant-based components. These materials were selected for their proven efficacy in capturing air pollutants and their availability in low-income settings, making them suitable for the target population.

Throughout the six-month study period, the durability of the filter boxes was meticulously assessed through monthly site visits. Researchers conducted detailed inspections to monitor the physical condition of the filters. The filter boxes generally displayed commendable durability.

The biochar and plant-based materials maintained their effectiveness and structural integrity over the duration of the study. The filters exhibited minor signs of wear, such as superficial scratches on the exterior and slight loosening of some components. However, these issues did not significantly compromise the performance or functionality of the filters.

A critical element of durability was the condition of the biochar used in the filters. Biochar, renowned for its high adsorption capacity, can potentially degrade if it becomes saturated with indoor air pollutants. To address this, the filters were designed to facilitate easy replacement of the biochar.

Monthly inspections confirmed that the biochar retained its adsorption capability, with minimal signs of degradation. Participants adhered to the scheduled replacement of biochar, ensuring the filters continued to operate effectively throughout the study period.

Repairs to the filter boxes were infrequent and generally minor. Occasional repairs involved tightening screws or securing loose parts. The low frequency of repairs indicated that the filters were robust and that the design effectively minimised physical wear and tear.

Additionally, the maintenance tasks required to keep the filters in good condition were straightforward and manageable. Participants were able to perform these tasks with minimal difficulty, contributing to the overall durability of the filters.

The maintenance process, including cleaning the filter surfaces and replacing biochar, was designed to be simple and efficient. Participants were provided with clear instructions on how to carry out these tasks, and adherence to the maintenance schedule was generally good. The ease of maintenance played a crucial role in ensuring that the filters remained durable and functional over the six-month study period.

The usability of the nature-inspired air filter boxes was assessed through a combination of direct observation and participant feedback. The aim was to evaluate how seamlessly participants could integrate the filters into their daily routines and manage them effectively.

Researchers observed that the installation process for the filter boxes was user-friendly. Most participants were able to install the filters independently, with an average installation time of approximately 20 minutes. The design included straightforward, user-friendly instructions, which facilitated a smooth setup process. The filters were designed to be versatile and adaptable to various household settings, contributing to the ease of installation.

Maintenance tasks were another key focus of the usability evaluation. Participants were required to clean the filter surfaces on a monthly basis and replace the biochar every three months. These tasks were intentionally designed to be simple and did not require specialised tools or technical expertise.

Observations revealed that participants generally managed these tasks effectively. The low maintenance requirements were well received, as they did not impose a significant burden on participants' daily routines.

Surveys administered at the beginning, middle, and end of the study provided valuable insights into participants' experiences. The surveys explored aspects such as the ease of installation, maintenance requirements, and perceived improvements in IAQ. Results showed that a high percentage of participants found the installation process to be straightforward.

Maintenance tasks were deemed manageable by the majority of participants, who appreciated the simplicity and infrequency of the required upkeep. Additionally, participants reported noticeable improvements in IAQ, with many indicating a significant positive impact on their living conditions.

Focus group discussions conducted at the study's conclusion offered further qualitative feedback on the usability of the nature-inspired air filter boxes. Participants shared their experiences and opinions on how well the filters fit into their daily lives.

Overall, participants expressed satisfaction with the effectiveness of the nature-inspired air filters in improving IAQ and the ease of use. Many indicated a willingness to continue using the filters in the future, suggesting a high level of acceptance and satisfaction with the product.

The detailed evaluation of the nature-inspired air filter boxes in terms of durability and usability revealed that the filters performed well in maintaining their functionality and integrating smoothly into users' routines. The robust materials and user-friendly design contributed to positive outcomes, demonstrating the practicality and effectiveness of the nature-inspired air filters in improving IAQ.

—Health Impact Assessment—

During the study, baseline health data revealed widespread respiratory and cardiovascular symptoms among participants. Frequent complaints included coughing, wheezing, shortness of breath, eye irritation, headaches, and cardiovascular issues. This initial data provided a vital reference for tracking changes in health throughout the study.

Over the six-month period, the intervention group, using nature-inspired air filter boxes, reported a marked improvement in health. Respiratory symptoms, such as coughing and wheezing, dropped by 35%, while shortness of breath among children and the elderly decreased by 28%. Reports of headaches and eye irritation declined by 23%, indicating an overall enhancement in IAQ-related health conditions.

In contrast, the control group, which experienced no improvement in IAQ, saw no significant changes in health symptoms. Respiratory complaints remained stable, and cardiovascular issues persisted, underscoring the effectiveness of the intervention in reducing health risks associated with indoor air pollutants.

Objective health measurements supported these findings. Lung function tests showed an 18% increase in forced expiratory volume (FEV1) and forced vital capacity (FVC) among intervention group participants. Blood oxygen levels also improved by 12%, further validating the positive impact of the air filters on respiratory health.

Modelling of long-term health outcomes based on these improvements suggested that continued use of the nature-inspired filters could lead to a 45% reduction in asthma incidence and chronic bronchitis over five years.

The reduction of fine particulate matter and volatile organic compounds (VOCs) was expected to play a significant role in preventing these conditions. Additionally, the risk of cardiovascular issues was projected to decline by 33%, potentially reducing instances of heart attacks and hypertension.

Economic benefits were also projected, with fewer doctor visits, reduced medication use, and lower hospitalisation rates anticipated due to the improved air quality. The filters were expected to enhance the quality of life, promoting better physical activity, sleep, and overall well-being.

In conclusion, the study's health impact assessment demonstrated the air filters' positive influence on respiratory and cardiovascular health. The intervention group experienced significant improvements in both subjective health symptoms and objective measurements, while long-term modelling indicated promising reductions in chronic health conditions. These findings highlight the potential for widespread health benefits through the use of nature-inspired air filters, especially in polluted environments, at a price they can afford.

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Before my PhD qualifying exam, I had married a remarkable woman, a brilliant early childhood educator whom I had met during my undergraduate years. She was completing her MSc in Early Childhood Education, and her deep compassion and intelligence became a wellspring of inspiration for me. We met through friends and developed friendship.

We began our life together, navigating the challenges of academia and parenthood as we welcomed our daughter into the world shortly after our marriage. Our daughter, with her boundless curiosity and vibrant spirit, brought immeasurable joy into our lives and became the anchor of our shared purpose.

After completing my PhD, life unfolded in unexpected yet profoundly meaningful ways. I was awarded the prestigious University of Solterra Overseas Postgraduate Fellowship. Upon being awarded the Fellowship, I set out for Phonebridge University in Ingland, United Empire, to begin my postdoctoral research.

This opportunity, a distinguished honour, came with the expectation that I would return to Solterra as an Assistant Professor after completing my postdoc, a responsibility I wholeheartedly embraced.

At Phonebridge, my research flourished, focusing on integrating advanced material science and engineering into innovative solutions for improving IAQ. My work extended far beyond the confines of the laboratory or scholarly publications.

During my time at Phonebridge University, I had the extraordinary opportunity to lead a project that extended my PhD research in material science and engineering to a real-world IAQ application. This initiative, in collaboration with several NGOs, focused on reducing the exposure of vulnerable populations to hazardous indoor air pollutants in low-income countries.

It was a continuation of the work I had done during my doctoral studies, where I explored the integration of advanced material science and engineering into practical, low-cost solutions for improving IAQ. My research, which focused on developing innovative materials to filter and absorb air pollutants, provided the foundation for this project.

The project's central goal was to create affordable filtration systems for homes and schools using locally sourced materials. Building on the principles I had developed during my PhD, we designed systems that were not only effective at removing particulate matter and toxic chemicals from the air but were also accessible to communities with limited financial resources.

These systems incorporated natured inspired air filters–an idea born from my doctoral work–using materials with high adsorption capacities to trap harmful indoor air pollutants. Additionally, the ventilation systems we implemented were simple yet effective, tailored to the specific needs of each community.

The impact in my homeland, Pamsia, was especially meaningful. Leveraging the findings from my PhD research, which demonstrated how certain low-cost materials could be optimised for air pollutant removal, we retrofitted homes and schools with these low-cost air cleaning system. The project went beyond technology–it involved working closely with local governments and community leaders to ensure the interventions were culturally appropriate and sustainable.

One of the key lessons from my PhD research was that scientific solutions must be adaptable to local contexts to be successful. This understanding shaped our approach, ensuring the systems were easy to maintain and that community members were empowered to manage their IAQ long after our team left.

The results were staggering. In Pamsia, families reported a significant reduction in respiratory illnesses, a clear indication of the effectiveness of the filtration systems. Children, who had previously been missing school due to illness, were able to attend more regularly, and awareness of the importance of IAQ spread throughout the communities we worked with. These outcomes validated the findings of my PhD research, demonstrating that material science could be a powerful tool in addressing global health challenges, especially in resource-limited settings.

One of the most profound aspects of this experience was the realisation that my research had a tangible impact on people's lives. While the academic community recognised my work through publications and awards, it was the visible improvements in health and well-being that fuelled my passion. The success of our interventions in Pamsia and other low-income countries confirmed that my research could transcend the confines of academia and make a real difference in the world.

As demand for my expertise grew, I expanded the project's reach beyond Pamsia. We trained local engineers and technicians in low-income countries, sharing the knowledge from my PhD research and enabling these communities to implement the same low-cost IAQ solutions. The ripple effect of this work was immense.

Communities that had once been vulnerable to hazardous air pollutants were now equipped with the tools and knowledge to protect their health. My PhD work, which began in the laboratory, had become a global movement toward cleaner, healthier indoor environments for the world's most at-risk populations.

This project solidified my belief that science, when applied with compassion and foresight, can be a transformative force for good. It was no longer just about the theoretical advancements I had made during my PhD; it was about how those advancements could change lives. This realisation guided the rest of my career, as I continued to focus on research that bridged the gap between scientific innovation and social impact.

When I returned to the University of Solterra as an Assistant Professor and formed my own research lab and team, the experiences I had gained in applying my research to real-world problems profoundly shaped my approach to academia. My journey through the practical implementation of low-cost IAQ solutions in low-income countries had broadened my perspective.

I was no longer solely focused on academic research. I had become a passionate advocate for the equitable distribution of clean air solutions worldwide. My research, initially rooted in material science and engineering and IAQ, now had a broader reach, influencing policy, education, and public health on a global scale.

At the University of Solterra, my work quickly attracted attention, not only for its technical merits but for the real-world impact it had demonstrated in improving public health in vulnerable communities. Governments and international organisations, recognising the success of the projects I had led in places like Pamsia, began to seek my counsel.

They invited me to contribute to policy discussions, asking for my expertise in crafting strategies to address the pressing challenges of air pollution, particularly in the context of public health. As I participated in these discussions, I found myself in a unique position–bridging the gap between scientific research and policy implementation, always with a focus on ensuring that my solutions remained accessible to those who needed them most.

However, despite these achievements and the growing recognition of my work, my personal motivations remained deeply grounded in my commitment to countless families in low-income countries who still suffered from the effects of poor IAQ. The personal connection to my work ensured that my research and initiatives were never just theoretical exercises–they were a force for tangible, positive change.

As I progressed through my academic career at the University of Solterra, my passion for teaching and research became intertwined. I was committed to ensuring that the knowledge I had gained through my projects would not remain within the confines of academia but would be shared widely to empower future generations.

Within a few years, I had risen to the rank of Associate Professor, driven by my belief in the transformative power of education and research to uplift communities. My work in IAQ and material science continued to evolve, now incorporating insights from my international collaborations and policy work, and I soon began mentoring students who shared my vision for creating a healthier world.

After several years of conducting groundbreaking research and leading impactful projects across various continents, I was promoted to full Professor. My reputation at Solterra grew alongside my influence in the global fight against air pollution. Solterra had become my second home, and as a naturalised Solterran citizen, I felt a deep sense of responsibility to give back–not just to the academic community but to society at large.

My role expanded beyond the university, and my expertise was increasingly called upon by international bodies concerned with global health and environmental sustainability, especially in low-income countries.

In recognition of my contributions to the field of IAQ, I was appointed as a special adviser to the World Health Organisation (WHO). In this capacity, I played a pivotal role in shaping global policies aimed at reducing indoor air pollution, particularly in developing nations. I advocated for the inclusion of low-cost, sustainable technologies–rooted in my own research–in international guidelines for safe indoor environments.

My work with the WHO helped to establish foundational policies that ensured vulnerable populations had access to the tools and knowledge needed to protect themselves from the dangers of indoor air pollutants. The guidelines we developed were instrumental in setting global standards for safe indoor air, particularly in areas where air quality was a critical public health issue.

My research had come full circle, from theoretical exploration to practical implementation, and finally to influencing global health policy. Throughout my time at the WHO, I remained deeply connected to my work at the University of Solterra.

As a full Professor, I continued to lead research projects that pushed the boundaries of material science and engineering, focusing on innovations that could further enhance IAQ. I also mentored a new generation of scholars who shared my commitment to applying scientific knowledge for societal good.

Many of my students went on to lead projects that replicated our success in low-income countries, working with local communities to develop sustainable solutions to indoor air pollution. My research efforts contributed to a growing awareness of the importance of IAQ in the broader discourse on environmental health and sustainability.

Ultimately, my journey–from a young researcher focused on material science, engineering, and IAQ to a global advocate for equitable IAQ solutions–reflected my belief that knowledge must serve a greater purpose.

Whether through academic research, policy advocacy, or hands-on community engagement, I remained dedicated to improving the health and well-being of families around the world, including my own. My work had come to symbolise the intersection of science, policy, and social impact, and it was this synergy that defined my career at the University of Solterra and beyond.

I worked closely with ministers and policymakers in Solterran, advocating for initiatives that prioritised both environmental sustainability and the health of the population. Each policy I helped shape was a step toward creating healthier, more resilient communities, and with each contribution, my influence expanded–not for personal gain but for the greater good.

The success of my work was deeply fulfilling, but what brought me the greatest joy was the ripple effect it had on my family. My parents, once humble farmers in Pamsia, now lived comfortably, proud of the legacy we had built together. My father, who had lost so much, and my mother, whose resilience held our family together, now witnessed the fruits of our collective perseverance.

My siblings, too, had thrived, excelling in their fields and unburdened by the financial hardships that once weighed us down. Together, we had lifted our family out of poverty, breaking the cycle for future generations.

In moments of reflection, I often thought of Mr. Carter, the man who had seen potential in me when I was nothing more than a construction labourer. He continued to visit, his pride in my achievements unmistakable. His faith in me had sparked a flame that would never die. “I always knew you had it in you,” he would say with a smile.

As I looked back on my journey–from leaving Pamsia with little more than hope to standing among world leaders and shaping global policies–I realised that my story was not just about my achievements. It was about the impact I had on the lives of others. My journey was a testament to the power of perseverance, intelligence, and compassion, and to the truth that success is not about individual accolades but about creating opportunities for others to rise as well.

The legacy I had built was not in titles or honours but in the lives I had touched, the communities I had uplifted, and the future I had helped shape for others. This was my greatest accomplishment: the knowledge that through love, sacrifice, and a commitment to making the world better, we could all rise together. **The End!**