Concept of mass balance modelling of an indoor air pollutant made easier: A case of secondary organic aerosol (SOA)

indooraircartoon.com/2025/02/26/concept-of-mass-balance-modelling-of-an-indoor-air-pollutant-made-easier-a-case-of-secondary-organic-aerosol-soa

26 February 2025

Indoor Air Cartoon Journal, February 2025, Volume 8, #163

[Cite as: Fadeyi MO (2025). Concept of mass balance modelling of an indoor air pollutant made easier: A case of secondary organic aerosol (SOA). *Indoor Air Cartoon Journal*, February 2025, Volume 8, #163.]

Indoor Air Cartoon
Indoor Air Cartoon
February 2025
Vol. 8
#163
Artistic-Educational Research

CONCEPT OF MASS BALANCE MODELLING OF AN INDOOR AIR POLLUTANT MADE EASIER: A CASE OF SECONDARY ORGANIC AEROSOL (SOA)

Thus, the exponential decay of the SOA concentration is expressed as: ②

$$e^{-(k_v+k_s+k_cC_{SOA}+k_f)t}$$

The remaining concentration of $C_{SOA,0}$ at time t is given by:

$$\boxed{C_{SOA,0}e^{-(k_v+k_s+k_cC_{SOA}+k_f)t}}$$

Suddenly, a person, aiming to improve IAQ and perceived air quality, sprays a limonene-based air freshener into the indoor environment.

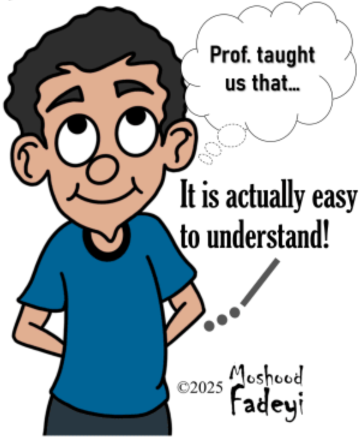
Start here ★ ①

Imagine an indoor environment contains a residual SOA concentration ($C_{SOA,0}$) from a now-inactive source. The concentration of the SOA will continue to decay exponentially, following the mathematical constant Euler's number (e^-), with an exponent determined by various removal processes: ventilation (k_v), deposition on surfaces (k_s), coagulation (k_cC_{SOA}), where particles stick together and reduce in number, and filtration (k_f), all occurring over time (t).

So, to reduce exposure to and concentrations of SOA, invest in reduction or elimination of source and its emission rate, and invest more in ventilation, airflow rate, and air cleaning systems.

The concept also applies to other indoor air pollutants, including ozone and limonene concentration formation.

Recalling the misleading promotion of ozone as an air purifier, the person also ③ introduces ozone into the room with an ozone generator. The simultaneous presence of ozone and limonene leads to a chemical reaction, since ozone is a powerful oxidizing agent, producing SOAs. The rate of reaction (k_r) between ozone (C_{O3}) and limonene (C_L) concentrations, and the formation rate, also known as yield rate (Y), of SOAs from the chemistry will determine the SOAs contribution rate ($Yk_rC_{O3}C_L$). ④



The contribution rate, i.e., volumetric source emission rate, ($Yk_rC_{O3}C_L$), of SOAs into the indoor environment by the active ozone-limonene chemistry will be simultaneously counteracted by the volumetric sink rate, i.e., removal rate ($k_v+k_s+k_cC_{SOA}+k_f$) in the indoor environment. This balance determines the concentration of SOA formed, which is expressed as:

$$\frac{Yk_rC_{O_3}C_L}{k_v+k_s+k_cC_{SOA}+k_f}$$

Volumetric source emission rate

Volumetric sink (i.e., removal) rate

This formula is based on the fundamental principle that the concentration of an indoor air pollutant being contributed by an active source is equal to the ratio of the volumetric source emission rate to that of sink rate in the indoor environment. However, as the new concentration of SOA is being formed, a fraction of it is expected to decay with time. The portion of the SOA concentration undergoing decay with time is expressed as:

$$\left(\frac{Yk_rC_{O_3}C_L}{k_v+k_s+k_cC_{SOA}+k_f}\right)e^{-(k_v+k_s+k_cC_{SOA}+k_f)t}$$

⑤

Thus, the portion of SOA concentration remaining due to the active source (ozone-initiated chemistry) at steady state is:

$$\frac{Yk_rC_{O_3}C_L}{k_v+k_s+k_cC_{SOA}+k_f}-\left(\frac{Yk_rC_{O_3}C_L}{k_v+k_s+k_cC_{SOA}+k_f}\right)e^{-(k_v+k_s+k_cC_{SOA}+k_f)t}$$

When factorised, the equation becomes:

$$\boxed{\frac{Yk_rC_{O_3}C_L}{k_v+k_s+k_cC_{SOA}+k_f}\left(1-e^{-(k_v+k_s+k_cC_{SOA}+k_f)t}\right)}$$

⑥ Therefore, the total SOAs concentration in the room at time (t) is the sum of remaining portion of the initial SOA concentration and the remaining portion of SOA concentration at steady-state. This is mathematically expressed as:

$$C_{\mathrm{SOA}}(t)=\boxed{C_{\mathrm{SOA},0}e^{-(k_v+k_s+k_cC_{\mathrm{SOA}}+k_f)t}}+\boxed{\frac{Yk_rC_{O_3}C_L}{k_v+k_s+k_cC_{\mathrm{SOA}}+k_f}\left(1-e^{-(k_v+k_s+k_cC_{\mathrm{SOA}}+k_f)t}\right)}$$

REFERENCES

Fadeyi, M. O., Weschler, C. J., and Tham, K. W. (2009). Atmospheric Environment, 43(22-23), 3538-3547.
Nazaroff, W. W., and Cass, G. R. (1989). Environmental Science & Technology, 23(2), 157-166.
Weschler, C. J., and Carslaw, N. (2018). Environmental Science & Technology, 52(5), 2419-2428.

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

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

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

……………………………………..

Indoor air quality (IAQ) education faces challenges in fostering students' critical and reflective thinking, abstract reasoning, logical deduction, creative imagination, and problem-solving skills, particularly in understanding secondary organic aerosol (SOA) transformations through mass balance modelling and other related IAQ concepts. Traditional lecture-based instruction relies on passive learning and equation-driven explanations, limiting students' ability to ask the right questions and construct meaningful connections between theoretical principles and real-world applications. Without foundational knowledge, structured mental models, and curiosity-driven exploration, students struggle with cognitive flexibility, leading to a fragmented understanding of real-life IAQ problems and the development of solutions to address them in a value-oriented manner.

Artificial Intelligence-driven gamification presents a promising solution by providing interactive, real-time problem-solving environments where learners can manipulate environmental variables, observe cause-and-effect relationships, and refine IAQ strategies dynamically. Despite its potential, research on how gamification enhances cognitive abilities and knowledge transfer in IAQ education remains limited. The lack of such research has hindered the application of gamification in IAQ education and practice. This limitation caught the attention of a boy who had experienced first-hand how students struggled to comprehend IAQ theoretical concepts and apply them to solving IAQ problems due to the traditional methods of teaching.

His appreciation for solving IAQ problems and enhancing people's cognitive abilities to solve them through effective education stemmed from his own childhood struggles. He dedicated his professional life to understanding how AI-based gamification learning environments could bridge the gap between the current state of IAQ education and practice and the goal of effective IAQ education, practice, and healthy indoor air delivery for all. The journey of this boy is the focus of this fiction story.

1……………………………………..

Adebanjo Kareem's childhood was shaped by love, sacrifice, and an unrelenting sense of duty. Born into a poor family in a small rural village, he was the only child of Mr. Adejobi Kareem and Mrs. Olabisi Kareem. His father worked as a construction labourer in the Middle East, sending money home every month, but it was never enough. Much of what he earned went toward purchasing Adebanjo's inhalers, his constant companion–a small device that kept him breathing and rescued him whenever his chest tightened, refusing to let air pass. The inhalers were expensive, leaving little for anything else. His mother often stretched the little money they had, prioritising her son's health above all else.

For most of his childhood, his father was an image on a screen, his voice distorted through video calls, offering encouragement from thousands of miles away. His visits home, though filled with joy, were fleeting–twice a year, no more. His mother, a resilient and determined woman, single-handedly raised him, making sacrifices he could never fully understand at the time. She had once been a petty trader, selling vegetables and food items to earn a living, but as Adebanjo's condition worsened, her focus shifted entirely to caring for him. She could not leave him alone for too long, not when every breath he took was a gamble.

From the moment he could grasp the meaning of words, his mother had instilled in him a singular belief–his education was his only way out. She told him this when he was too young to grasp its significance, whispered it into his ear as she plaited his hair before school, and repeated it as she wiped his face with a damp cloth before sending him off each morning. By the time he was nine years old, he no longer needed reminders. He believed it wholeheartedly.

Despite their struggles, Adebanjo was never an average child. He was sharp, observant, and eager to learn. His primary school was nothing more than a crumbling block of classrooms, with wooden benches and dusty blackboards. Teachers came and went, sometimes absent for days, but Adebanjo absorbed knowledge like a sponge. He was always the top of his class, praised by teachers and envied by classmates. Every test, every assignment, every lesson was another step toward his future–one he believed was entirely dependent on his ability to excel in school. However, there was something wrong with him, something he had ignored for years.

Adebanjo's problem was the air he breathed–but he did not understand it yet. From the time he was a child, he suffered from persistent coughing fits, wheezing episodes that left him gasping for air. It was not seasonal. It was not something that came and went–it was his everyday reality. His mother initially thought it was just harmattan allergies, caused by the dust filling the air during the dry season. However, as the years passed, she realised that harmattan was not the problem.

Adebanjo coughed in the rainy season. He coughed in the dry season. He coughed in the middle of the night, even when the air outside was cool and fresh. The worst of it came from their kitchen–a small, enclosed space where his mother cooked over a coal stove. Smoke curled into the air, lingering long after she finished cooking, coating the walls with soot, stinging Adebanjo's eyes, making him gasp for breath.

One evening, he sat on a stool in the corner of the kitchen, watching his mother cook. The thick smoke clung to everything, filling the small space with an oppressive weight. “Mama, why does it feel so hard to breathe in here?” he asked, his voice hoarse. His mother paused, glancing at him before turning back to the pot. “It's just the smoke, my dear,” she said, her voice heavy with exhaustion. “It will go away soon.” Yet, it never truly did.

However, the inhaler, always in his pocket, always gave him relief and made him function well. Thus, carrying his inhaler wherever he went became second nature to him. He thought little of his medical condition, as it had already become a part of his life and felt like a normal occurrence, one he believed he was in control of with the aid of his inhaler–until one day at school, his perspective changed forever. It was a science lesson in his final year of primary school, a rare day when the teacher arrived early, his chalk already tapping against the blackboard. He spokes of pollution–the black smoke that billowed from cars in the city, the factory fumes that clouded the air.

Adebanjo, always eager to learn, listened intently. Yet, a nagging thought lingered. He raised his hand. “Sir, is there pollution inside houses too?” The teacher paused, surprised. No one had ever asked him that before. He smiled and nodded. “Yes, my boy. Smoke from cooking, dust, poor ventilation–it all stays trapped inside. Some say it is even worse than outdoor pollution because we breathe it for longer.” Adebanjo felt a sharp jolt of understanding.

The cough that never left him had an explanation. His mother’s watery eyes when she cooked, the soot that darkened their walls, the breathlessness that sometimes overwhelmed him–it was all because of the air they lived in.

That night, as he lay coughing into his pillow, his inhaler by his side, he thought, “This is not normal. If this is a problem, why hasn’t anyone fixed it?” That was the first time he felt it–the frustration of knowing something was wrong yet lacking the power to change it.

Years passed, and Adebanjo never stopped thinking about that lesson. He devoured books, researching everything he could about air, pollution, and ventilation. Despite all his learning, helplessness lingered. What could he do with this knowledge? He was still a boy, still poor, still breathing the same unclean air, his inhaler always within reach. He excelled in science and mathematics, winning state-wide competitions and earning a reputation as the brightest student in his school. Yet, a clear path remained elusive.

It was not until his final year of secondary school, when he met an engineer from the city, that the answer came to him. The engineer had come to speak about career paths in STEM (science, technology, engineering, and mathematics), urging students to think beyond their village. He spoke of machines, designs, solutions–things that could change lives. Adebanjo listened intently, a fire igniting in his chest.

After the session, he approached the man. “Sir, can engineers fix the air in homes?” The man looked at him curiously. “What do you mean?” “I mean, can engineers stop the air from making people sick? Can they design homes with better ventilation? Can they make cooking safer?”

The man smiled. “Of course. That is what we do. Engineers solve problems.” At that moment, Adebanjo knew. He would become an engineer. Not a doctor. Not a lawyer. Not an accountant. An engineer. He would learn how air moved, how it could be cleaned, how homes could be designed for better ventilation.

The day he received his admission letter for mechanical engineering was the day his life truly began. His father, tired from years of working abroad, back to his country permanently wept with pride. His mother, who had sacrificed everything for him, held the letter to her chest and whispered, “You are going to change the world, my son.” Adebanjo knew she was right. He had no choice. Adebanjo knew she was right. He had no choice. Having breathed the problem for close to nineteen years, he was now ready to solve it.

Adebanjo Kareem was a standout student in his mechanical engineering programme. His professors recognised his sharp intellect, his classmates admired his ability to grasp complex concepts effortlessly, and his friends sought his help whenever they struggled with coursework.

However, it was in his Indoor Air Quality Engineering class that he first encountered a problem he could not ignore.

It started with a lecture on Secondary Organic Aerosol (SOA). The professor explained how these airborne particles formed from chemical reactions between VOCs and oxidants like ozone, contributing to indoor air pollution. The concept was complex, but for Adebanjo, it made sense. The professor had simplified the explanation, breaking it down step by step, and Adebanjo could see the logic in how SOAs transformed over time–through deposition, coagulation, ventilation, and filtration. An extract from the professor's lecture is as follows.

"Secondary organic aerosols (SOA) are airborne particles, primarily in the fine size range, formed indoors through the oxidation of volatile organic compounds (VOCs). Some start as ultrafine particles before growing into fine particles. SOA contribute to indoor air pollution and may pose health risks.

Research suggests SOA inhalation may impact respiratory, cardiovascular, and neurological health, potentially exacerbating asthma, triggering inflammation, and affecting cognition. Prolonged exposure may also influence metabolic function and increase chronic disease risk.

While some SOA components are suspected carcinogens, further studies are on-going to determine their specific health effects and long-term implications. In an indoor environment, the concentration of SOA can be modelled to guide decisions on reducing exposure. To help you understand this, let u's go through the mass balance modelling approach together.

Imagine an indoor environment contains a residual SOA concentration ($C_{\text{SOA},0}$) from a now-inactive source. The concentration of the SOA will continue to decay exponentially, following the mathematical constant Euler's number (e^{-}), with an exponent determined by various removal processes: ventilation (k_v), deposition on surfaces (k_s), coagulation ($k_c C_{\text{SOA}}$), where particles stick together and reduce in number, and filtration (k_f), all occurring over time (t). Thus, the exponential decay of the SOA concentration is expressed as:

$$e^{-(k_v+k_s+k_c C_{SOA}+k_f)t}$$

The remaining concentration of $C_{\text{SOA},0}$ at time t is given by:

$$C_{SOA,0}e^{-(k_v+k_s+k_c C_{SOA}+k_f)t}$$

Suddenly, a person, aiming to improve IAQ and perceived air quality, sprays a limonene-based air freshener into the indoor environment. Recalling the misleading promotion of ozone as an air purifier, the person also introduces ozone into the room with an ozone generator. The simultaneous presence of ozone and limonene leads to a chemical reaction, since ozone is a powerful oxidizing agent, producing SOAs. The rate of reaction (k_r) between ozone (C_{O3}) and limonene (C_L) concentrations, and the formation rate, also known as yield rate (Y), of SOAs from the chemistry will determine the SOAs contribution rate ($Yk_rC_{O3}C_L$).

The contribution rate, i.e., volumetric source emission rate, ($Yk_rC_{O3}C_L$), of SOAs into the indoor environment by the active ozone-limonene chemistry will be simultaneously counteracted by the volumetric sink rate, i.e., removal rate (k_v+k_s+k_cC_{SOA}+k_f) in the indoor environment. This balance determines the concentration of SOA formed, which is expressed as:

$$\frac{Yk_rC_{O_3}C_L}{k_v + k_s + k_cC_{SOA} + k_f}$$

This formula is based on the fundamental principle that the concentration of an indoor air pollutant being contributed by an active source is equal to the ratio of the volumetric source emission rate to that of sink (i.e., removal) rate in the indoor environment. However, as the new concentration of SOA is being formed, a fraction of it is expected to decay with time. The portion of the SOA concentration undergoing decay with time is expressed as:

$$\left(\frac{Yk_rC_{O_3}C_L}{k_v + k_s + k_cC_{SOA} + k_f}\right) e^{-(k_v+k_s+k_cC_{SOA}+k_f)t}$$

Thus, the portion of SOA concentration remaining due to the active source (ozone-initiated chemistry) at steady state is:

$$\frac{Yk_rC_{O_3}C_L}{k_v + k_s + k_cC_{SOA} + k_f} - \left(\frac{Yk_rC_{O_3}C_L}{k_v + k_s + k_cC_{SOA} + k_f}\right) e^{-(k_v+k_s+k_cC_{SOA}+k_f)t}$$

When factorised, the equation becomes:

$$\frac{Yk_rC_{O_3}C_L}{k_v + k_s + k_cC_{SOA} + k_f}\left(1 - e^{-(k_v+k_s+k_cC_{SOA}+k_f)t}\right)$$

Therefore, the total SOA concentration in the room at time (t) is the sum of remaining portion of the initial SOA concentration and the remaining portion of SOA concentration at steady-state. This is mathematically expressed as:

$$C_{\mathrm{SOA}}(t) = C_{\mathrm{SOA},0}e^{-(k_v+k_s+k_cC_{\mathrm{SOA}}+k_f)t} + \frac{Yk_rC_{O_3}C_L}{k_v + k_s + k_cC_{\mathrm{SOA}} + k_f}\left(1 - e^{-(k_v+k_s+k_cC_{\mathrm{SOA}}+k_f)t}\right)$$

Understanding the mass balance modelling equations of the reactants—ozone and limonene—will aid in controlling their concentrations. The concept of SOA mass balance modelling, as explained, can be applied to ozone, limonene, and other air pollutants in indoor environments. As evident from the provided mass balance models for ozone and limonene, they follow the same pattern as the SOA mass balance model.

It is important to model ozone and limonene (VOCs) generated in indoor environments because understanding the dynamics of their concentrations will aid in a better understanding of the dynamics of calculated or measured concentrations of these reactants and that of SOA.

The mass balance modelling equation for ozone is:

$$C_{O_3}(t) = C_{O_3,0}e^{-(k_v+k_s+k_r+k_f)t} + \frac{S_{O_3}}{k_v + k_s + k_r + k_f}\left(1 - e^{-(k_v+k_s+k_r+k_f)t}\right)$$

S_{O3} is the ozone emission rate from the source. K_r represents the constant rate at which ozone is lost due to its reaction with limonene. Note that other VOCs present in the room may also contribute to the ozone loss rate through chemical reactions. However, their effect will be assumed to be negligible if their concentrations in the room are minimal, while limonene is deliberately injected into the room.

The mass balance modelling equation for limonene is:

$$C_L(t) = C_{L,0}e^{-(k_v+k_s+k_r+k_f)t} + \frac{S_L}{k_v + k_s + k_r + k_f}\left(1 - e^{-(k_v+k_s+k_r+k_f)t}\right)$$

S_L is the limonene emission rate from the source. K_r means the constant rate at which limonene is loss due to reaction with ozone.

Note that the loss of air pollutants by air filter (k_f) over time is determined by clean air delivery rate (CADR). CADR equation is expressed as:

[CADR = Airflow rate (m^3/min) x filtration efficiency]

Where filtration efficiency is represented as η.

$$\eta = \frac{C_{\text{in}} - C_{\text{out}}}{C_{\text{in}}} \times 100\%$$

C_{in} is the concentration before the filter; and C_{out} is the concentration after the filter. The airflow rate is the rate at which a volume of air (m^3) is entering or passing through air cleaning system per unit time (min^{-1}).

The rate of loss of air pollutants due to ventilation rate (k_v) over time is determined by ventilation rate equation expressed as:

$$ACH = \frac{60 \times Q}{V}$$

Where ACH (air changes per hour, h^{-1}) is a measure of how many times the indoor air is replaced by outdoor air per hour. Q represents the volume of outdoor air (m^3) supplied to or exhausted from a space per unit time (min^{-1}). V is the volume of the space (m^3). The factor 60 is used to convert minutes to hours because Q is given in cubic meters per minute (m^3/min), and ACH needs to be expressed per hour.

The rate at which air pollutants are lost due to deposition on indoor surfaces, known as surface deposition (k_s), depends on the total airflow rate in the room. The total airflow rate is influenced by flow rate of outdoor air entering the space and/or recirculated indoor air. Generally, the higher the airflow rate, the higher the surface deposition rate (k_s). In addition to the surfaces of inanimate objects or materials in the indoor environment, humans and animals present in the indoor environment can also serve as surfaces onto which air pollutants deposit through dermal uptake.

The rate at which the number concentration of SOA (i.e., the count of SOA particles in a unit volume of air) decreases depends on how frequently individual SOA particles collide and combine to form larger particles, a process known as coagulation. This means that an increase in the coagulation rate reduces the number (i.e., count) of standalone particles in the air. The rate of reduction is known as loss rate due to coagulation ($k_c C_{SOA}$).

However, as coagulation occurs—meaning smaller particles merge to form larger ones—the mass of each newly formed, larger particle increases. In other words, the mass concentration of a newly formed, larger particle will be higher than that of an individual, smaller particle before coagulation.

As the mass of a particle increases, it becomes heavier, making it more likely to settle on indoor surfaces due to air movement in the room and gravitational force. This means that an increase in the total airflow rate can indirectly enhance the surface deposition of larger particles formed through coagulation more than that of smaller particles. This will further reduce the number (i.e., count) of SOA particles in a unit volume of air.

Lest I forget, it is important to note that the total K (summation of all the loss rates) will depend on the relevant phenomena considered, which contribute to the decay or sink (i.e., removal) of pollutants from indoor air.

Please note that ventilation, known to be a sink, can also be a source of air pollutants in the indoor environment if the outdoor air coming into the indoor environment is polluted with air pollutants. The same applies to air filters or other air cleaning systems. They can also be a source of air pollutants, either due to the nature of the air cleaning system or poor maintenance and operation of it.

That means that ventilation and air cleaning can simultaneously be a source and a sink. What we want is for the source effect to be as minimal as possible or the sink effect to be significantly higher than the unavoidable source effect. Unavoidable is the operative word here. If you have the capability of avoiding the air pollutant source effect of ventilation or air cleaning systems (including air filters), avoid it as much as possible.

The use of highly efficient and well-maintained air filters can significantly help reduce the burden effects that polluted outdoor air would have on indoor air, thus enhancing the benefit inherent in ventilation by ensuring that the sink effect of ventilation through the dilution phenomenon is significantly higher than any possible indoor air pollutant source effect caused by the polluted outdoor air."

As the professor was explaining, Adebanjo thought to himself, "It is actually easy to understand! So, to reduce exposure to and concentrations of SOA, invest in reducing or eliminating the source and its emission rate, and invest more in ventilation, airflow rate, and air cleaning systems. The concept also applies to other indoor air pollutants, including ozone and limonene concentration formation."

As the professor concluded the explanation of mass balance models and posed questions to the class, silence filled the room. Adebanjo turned to his classmates, expecting them to discuss how SOAs behave dynamically, how different IAQ strategies might reduce their concentrations, or how mass balance equations could model their behaviour. Instead, most sat quietly, flipping through their notes, trying to memorise equations without grasping their significance. Adebanjo answered the professor's questions and engaged in discussions with him.

After class, a few students approached Adebanjo for help. "How did you understand it so well?" one of them asked, sounding frustrated. "I get the equations, but I don't see how this applies to real life." Another added, "The professor said SOAs are affected by ventilation, but I don't really see it. If I increase ventilation, does that always mean fewer SOAs? Won't it depend on something else?"

Adebanjo sighed. He saw the problem clearly—his classmates were not engaging deeply with the concepts. They were not asking the right questions. They were simply treating SOAs as static entities rather than dynamic systems. They memorised the equations but did not visualise what those equations meant in an actual indoor environment.

For the next hour, Adebanjo tried to explain. He used real-world analogies, drew diagrams, and even walked them through a hypothetical office building scenario where different IAQ strategies could either increase or decrease SOA levels. But even then, he could see their struggle—without being able to see these processes in action, his classmates could not fully grasp how SOAs behaved. At that moment, a thought struck him: If some of the brightest students in my class can't visualise this, then the problem isn't them—it's how they are being taught.

Adebanjo began reflecting on the way IAQ concepts were taught. Most lessons followed the same pattern: a lecture-heavy approach, filled with complex derivations and static equations; no visualisation tools, leaving students unable to picture SOA transformations in real time; no room for curiosity, as students memorised formulas instead of asking meaningful questions. He realised that traditional IAQ education was not fostering deep learning. Students were learning facts but not understanding systems.

2.……………………………………..

One evening, while researching different teaching methods, Adebanjo came across a paper discussing gamification-based interactive learning. The idea fascinated him—a digital simulation where students could manipulate conditions in real time, tweak variables, and observe how outcomes transformed dynamically.

The game-based elements in gamification, as he understood them, refer to specific interactive features typically found in games but applied in education to enhance engagement, learning, and problem-solving skills. However, in his subsequent research, he was struck by the realisation that the concept of gamification had never been applied to IAQ education.

“This is what is missing,” he thought. “If students could experiment with IAQ systems, they would not just memorise equations–they would actually understand how pollutants behave. They would learn to ask the right questions.”

Adebanjo was already considered one of the best students in his class, and many expected him to take a lucrative engineering job after graduation. But the more he thought about it, the clearer his true passion became.

He did not just want to understand IAQ himself–he wanted to help others understand it too. He wanted to break down the barriers preventing students from developing critical and reflective thinking, abstract reasoning, logical deduction, and creative imagination in IAQ education.

Instead of merely studying IAQ problems, he sought to solve an educational challenge–transforming how IAQ was taught. That was when he decided to pursue an applied research PhD focused on developing a gamification-based interactive learning environment for IAQ education and practice. His frustration with how IAQ concepts were taught had set him on a path to find a better way and a clear vision for his future. However, there was a business he needed to handle first. That is, to successfully complete his undergraduate studies.

He poured himself into his final year of study. His days were long, his nights even longer. The rigorous nature of mechanical engineering at his university meant that there were countless assignments, practical sessions, and projects to complete. While many students focused solely on getting through the coursework, Adebanjo had an additional mission–to deeply understand IAQ and how to improve its education. He scoured research papers on SOA transformations and other IAQ related topics, studied pedagogical strategies in engineering education, and even started working on early concepts for an interactive IAQ learning tool in his free time.

Adebanjo was not just a researcher in the making–he was also a student with exams to pass. His approach to studying was thorough and methodical. He developed mental models to connect theoretical principles with their applications, ensuring he understood every formula and equation as part of a broader system rather than isolated concepts.

When he was not buried in textbooks or working on his research ideas, he was helping his classmates. They would gather in small study groups, where Adebanjo would break down difficult topics, simplifying complex equations and turning abstract theories into relatable, real-world scenarios. He chose his undergraduate dissertation to be on IAQ for a better understanding of the subject.

By the time final year results were released, it was no surprise to anyone that Adebanjo had graduated with First Class Honours, earning an impressive 4.72 out of 5.00 CGPA–one of the highest in his graduating class. His professors celebrated his achievement, recognising not just his academic brilliance but his dedication to knowledge and his ability to inspire others. His classmates, many of whom had relied on his explanations to understand the toughest courses, congratulated him with admiration.

Yet, despite this major achievement, Adebanjo knew his journey had only just begun. He had a vision–to revolutionise IAQ education through gamification and interactive learning–and to do that, he needed to further his studies. A PhD was the next step, and he was determined to pursue it at a world-class university.

Applying for a PhD, however, was no simple feat. He spent weeks refining his statement of purpose, clearly articulating why IAQ education needed to change and how his research would bridge the gap between theoretical instruction and real-world application. He sought out highly ranked universities with strong research programmes in IAQ, environmental engineering, and educational technology.

The real challenge was funding. A PhD at a top university overseas required significant financial support, and Adebanjo knew he needed a competitive scholarship to make it possible. He meticulously prepared his applications, ensuring that every document–his academic transcripts, research proposal, recommendation letters, and personal statement–reflected not just his qualifications, but his passion for solving an educational problem that affected so many students like him.

It was a nerve-wracking process. He submitted applications to multiple institutions and waited. Some responses took weeks, others months. There were moments of doubt, but he reminded himself why he had chosen this path in the first place.

One evening, while sitting at his desk, his laptop screen lit up with a new email notification. It was from Whitehouse University in the United States of Abylon (USA), one of the highest-ranked universities in the world, known for its cutting-edge research in engineering and environmental sciences. With slightly trembling hands, he opened the email.

“*Dear Mr. Kareem*,

We are pleased to inform you that you have been awarded the Whitehouse International Doctoral Scholarship, covering full tuition and a generous research stipend. Your application stood out among a highly competitive pool of candidates, and we believe your research has the potential to make a significant impact in IAQ education and practice. We look forward to welcoming you to our PhD programme this fall.”

For a moment, Adebanjo just stared at the screen, hardly believing what he was reading. He had done it. He had secured a place at one of the best universities in the world, with a fully funded scholarship, to pursue the research that had been driving him for the past two years.

Excitement coursed through him as he called his parents, who could hardly contain their joy. His father, always a man of few words, simply said, “We are proud of you, son.” His mother, on the other hand, could not stop singing praises. His friends, his former professors, and even the classmates he had helped along the way sent congratulatory messages, all recognising that this was not just a personal achievement, but a victory for someone who truly cared about making education better.

That night, as he lay in bed, staring at the ceiling, his mind raced with ideas. Soon, he would be at Whitehouse University, USA, working alongside some of the brightest minds in IAQ research and engineering education. He would have access to state-of-the-art laboratories, world-class professors, and advanced computational tools to develop the gamification-based learning environment he had envisioned.

His journey had begun with a simple realisation–that students struggled with IAQ concepts because they could not visualise them. Now, he was about to embark on a journey to change that forever. As he closed his eyes, he smiled. The dream was real. And this was just the beginning.

Upon starting his PhD programme, Adebanjo refined his ideas and structured them into a research question: “How can an artificial intelligent (AI) gamification-based interactive learning environments enhance students’ ability to ask the right questions necessary for developing higher-order cognitive skills in IAQ education and practice?” His research problem became clear. Below is an excerpt from the research problem that shaped Adebanjo’s study.

“IAQ education faces a fundamental challenge in developing students’ critical and reflective thinking, abstract reasoning, logical deduction, and creative imagination, particularly in understanding the dynamic behaviour of secondary organic aerosols through mass balance modelling.

The primary barrier to cognitive development in this domain is the inability of students to ask the right questions necessary for enhancing these cognitive abilities. This limitation arises from a lack of basic knowledge, underdeveloped mental models, and insufficient curiosity, which prevents students from engaging deeply with SOA transformation mechanisms and real-world IAQ problem-solving.

Traditional IAQ education relies heavily on lecture-based instruction, equation-driven explanations, and passive learning approaches, which often fail to develop the mental frameworks necessary for inquiry-driven learning. Since SOA transformations involve complex interactions between ventilation, deposition, coagulation, filtration, and chemical reactions, understanding them requires a systems-thinking approach where students can see how different variables interact dynamically.

However, without foundational knowledge and structured mental models, students are unable to formulate insightful questions, explore causal relationships, or construct logical connections between theoretical principles and their practical implications. This leads to rote learning rather than deep conceptual mastery, making it difficult for learners to develop the reasoning skills necessary to apply mass balance principles effectively.

Moreover, the lack of curiosity-driven exploration in traditional pedagogical methods restricts students' ability to engage in hypothesis generation, problem formulation, and conceptual refinement, all of which are essential for scientific reasoning and real-world decision-making.

Since students are not encouraged to question, test, and iteratively refine their understanding, they struggle to develop the cognitive flexibility needed to tackle novel IAQ challenges. This results in a fragmented understanding of mass balance modelling, where students can manipulate equations but fail to conceptualise their real-world significance.

AI gamification-based interactive learning environments offer a promising solution by providing real-time engagement, dynamic visualisation, and experiential problem-solving that actively encourage students to ask the right questions. By enabling learners to manipulate environmental variables, observe real-time cause-and-effect relationships, and iteratively adjust IAQ management strategies, these tools foster the development of cognitive abilities necessary for advanced reasoning and problem-solving.

Despite these potential advantages, empirical research on how gamification influences the ability to ask the right questions, overcome cognitive barriers, and enhance higher-order thinking in IAQ education remains limited. Additionally, the extent to which interactive learning tools improve students' conceptual depth, decision-making processes, and capacity for knowledge transfer compared to traditional methods is not well understood.

This research addresses this gap by investigating how gamification-based interactive learning environments can enable students to ask the right questions, thereby enhancing their critical and reflective thinking, abstract reasoning, logical deduction, and creative imagination in understanding and applying mass balance principles to SOA transformations. The study seeks to determine whether interactive simulations facilitate deep learning, conceptual engagement, and real-world problem-solving skills, allowing students to transition from theoretical knowledge to applied IAQ management."

The research questions and problems informed the objectives of his PhD research. The objectives were: (i) To develop an AI gamification-based interactive learning environment that enhances students' ability to ask insightful questions necessary for higher-order cognitive skills in IAQ education and practice. (ii) To evaluate the effectiveness of interactive simulations in fostering critical and reflective thinking, abstract reasoning, logical deduction, and creative imagination in understanding IAQ concepts, particularly SOA transformations. (iii) To compare the impact of gamification-based learning and traditional lecture-based instruction on students' ability to formulate meaningful scientific inquiries, engage in problem-solving, and apply IAQ principles to real-world scenarios.

Adebanjo’s PhD research was supervised by the famous and word renowned professor of engineering education, Professor Anita Lagos. Below is an excerpt from Adebanjo’s PhD thesis.

3.……………………………………..

Research methods

A quasi-experimental research design was employed. This design provided a structured framework for systematically assessing cognitive development by measuring students’ learning outcomes before and after exposure to each instructional method. The use of a quasi-experimental approach was necessary due to the constraints of the educational setting, where complete randomisation of students across different instructional methods was not feasible. However, robust random assignment techniques were implemented to ensure that both groups were statistically equivalent before the intervention.

— *Participant Selection and Randomisation* —

The study was conducted in a university setting, drawing participants from undergraduate and graduate students enrolled in indoor air quality and environmental engineering courses. To maintain the highest scientific rigour, students were recruited from multiple universities, ensuring that the sample was not homogeneous in terms of academic preparation, institutional learning styles, and prior exposure to environmental science concepts. This multi-institutional approach minimised biases associated with a single university’s pedagogical strategies and allowed for greater generalisability of the findings.

Since participants were required to have no prior knowledge of mass balance modelling, a pre-screening test was administered to assess their familiarity with basic environmental engineering principles, differential equations, and indoor air quality concepts.

This test ensured that students possessed sufficient foundational knowledge in mathematics and physics to engage with mass balance equations but had not previously been introduced to the specific theoretical framework of mass balance modelling. Students who demonstrated pre-existing knowledge of pollutant transport equations or had coursework experience involving mass balance applications were excluded from the study to maintain the integrity of the experimental design.

A stratified random sampling method was employed to balance the distribution of students based on their academic standing (undergraduate versus graduate), prior coursework in indoor air quality, and self-reported familiarity with mathematical modelling principles.

Stratification ensured that both the experimental and control groups contained an equal proportion of students at different levels of study, preventing skewed distributions that could confound learning outcomes due to differences in academic maturity and prior technical expertise.

Participants were then randomly assigned to one of two groups: the experimental group, which engaged with an AI gamified learning environment, and the control group, which received instruction through traditional lectures. The randomisation process was conducted using a computerised randomisation algorithm to eliminate instructor bias.

Given that students' baseline knowledge levels could influence learning outcomes, all participants completed a pre-test prior to instruction. The pre-test assessed their understanding of fundamental scientific concepts relevant to SOA modelling (such as conservation laws, reaction kinetics, and indoor pollutant transport) but deliberately excluded direct exposure to mass balance principles. Cognitive abilities related to problem-solving and analytical reasoning were also measured, particularly their ability to identify causal relationships in environmental systems.

The results of the pre-test were analysed to ensure that there were no statistically significant differences in baseline knowledge between the experimental and control groups. Since all students lacked prior exposure to mass balance modelling, this test primarily served to confirm that both groups were comparable in their broader environmental science knowledge and problem-solving abilities before the intervention.

— *Lecture Structure and Instructional Approach* —

The traditional lecture-based instruction was structured to systematically introduce students to the principles of SOA mass balance modelling using established pedagogical techniques. The instructional format consisted of three weekly sessions of two hours each over a six-week period, conducted in a university classroom setting. Since the participants had no prior knowledge of mass balance modelling, the instructional content was sequenced in a progressive manner, beginning with fundamental scientific principles before transitioning into complex mathematical formulations and real-world applications.

The instructional method followed a deductive approach, in which students were first introduced to general conservation laws governing air pollutant transport and transformation, before engaging in detailed derivations of mass balance equations specific to SOA. Faculty members with expertise in indoor air quality modelling delivered the instruction, ensuring that the pedagogical approach was uniform across all participating institutions.

The lectures incorporated a combination of PowerPoint presentations, chalkboard derivations, and instructor-led discussions. PowerPoint slides were used to provide structured explanations and visual representations of pollutant transport mechanisms, including diagrams illustrating indoor air exchanges, SOA formation pathways, and removal processes.

The chalkboard was used for step-by-step derivations of governing equations, allowing students to see the logical progression of mathematical formulations. Instructor-led discussions encouraged students to ask questions and engage in dialogue regarding the theoretical principles underpinning SOA mass balance modelling.

To reinforce theoretical understanding, students were provided with printed lecture notes and supplementary readings from peer-reviewed IAQ literature, covering experimental studies and real-world applications of mass balance models. These readings were assigned as pre-lecture materials, ensuring that students entered the classroom with a foundational understanding of the topics to be discussed.

Mathematical and Theoretical Framework: A major component of the lecture-based instruction was dedicated to developing the mathematical formulations that describe SOA transformation and removal processes. Since students had no prior exposure to mass balance equations, instruction began with the derivation of the general mass balance equation, which describes the temporal evolution of air pollutant concentrations as a function of source emissions, transformation mechanisms, and removal processes.

The derivation process was structured to ensure that students understood each component of the governing equations. The ventilation rate term was introduced first, demonstrating how air exchange influences SOA concentrations by diluting pollutants over time. Deposition mechanisms were then introduced, explaining how particles adhere to surfaces and are removed from the indoor air.

The concept of coagulation was discussed, using kinetic models to illustrate how SOAs collide and form larger particles, altering their number concentration. Air filtration was introduced as an additional removal mechanism, with students learning how different filtration efficiencies affect mass balance calculations.

The reaction kinetics governing the oxidation of limonene by ozone were explained using rate equations that describe precursor depletion and SOA formation. Students were guided through calculations demonstrating how SOA formation depends on precursor concentrations, reaction rate constants, and environmental conditions. The derivations included assumptions, boundary conditions, and real-world parameter values obtained from IAQ literature, ensuring that students could contextualise the theoretical models within applied scenarios.

Problem-Solving Sessions and Case Studies: Following the theoretical instruction, students participated in problem-solving sessions that required them to apply mathematical formulations to real-world IAQ case studies. These sessions were structured to guide students through progressively more complex applications of mass balance modelling. The instructor first presented a case study describing an indoor environment with high SOA concentrations due to ozone-limonene chemistry. Students were tasked with developing mass balance equations for the system, identifying relevant source and sink terms, and solving for steady-state and transient pollutant concentrations.

Students worked individually on computational exercises before engaging in collaborative discussions with their peers. The problem sets required students to conduct sensitivity analyses, examining how changes in ventilation rates, filter efficiencies, and chemical reaction kinetics influenced SOA concentrations. Additional case studies involved estimating the relative contributions of primary and secondary aerosol sources in an indoor setting, requiring students to develop source attribution models based on given input data.

The instructor provided step-by-step guidance during the problem-solving sessions, highlighting common pitfalls and alternative solution methods. After completing the exercises, students were encouraged to present their results to the class, facilitating peer learning and collective discussion of analytical approaches.

Challenges and Limitations: The traditional lecture-based instruction relied on static representations of dynamic SOA transformation processes, requiring students to mentally conceptualise pollutant behaviour rather than engaging with real-time simulations. While step-by-step mathematical derivations provided a strong foundation for analytical reasoning, the absence of interactive visualisation tools meant that students had to rely on mental models to understand the effects of simultaneous transformation and removal mechanisms.

Manual computation was an integral component of the problem-solving sessions, requiring students to apply algebraic manipulations and numerical methods to solve for pollutant concentrations under different conditions. Since real-time feedback was not available, students had to complete full computations before verifying their results, limiting opportunities for immediate correction of conceptual misunderstandings. This approach required students to develop a strong procedural understanding of mass balance equations but did not inherently facilitate intuitive reasoning about how environmental conditions influence SOA dynamics in real-world settings.

Assessment and Evaluation: Students in the lecture-based instruction group completed a post-test assessment at the conclusion of the instructional period to evaluate their knowledge retention, conceptual understanding, and problem-solving abilities. The assessment mirrored that of the gamified learning group to ensure comparability between instructional methods. The test consisted of multiple-choice and open-ended questions that evaluated students' comprehension of SOA formation and removal mechanisms, as well as mathematical modelling tasks requiring them to apply mass balance equations to indoor air quality scenarios.

Concept mapping was also used to assess students' cognitive development. Prior to instruction, students constructed concept maps representing their understanding of SOA interactions, which were then compared to post-instruction maps to evaluate changes in knowledge structure. The maps were analysed based on their complexity, logical coherence, and the integration of key mass balance modelling concepts.

To gain qualitative insights into students' learning experiences, structured discussion sessions were conducted at the end of the instructional period. Students were asked to articulate their understanding of SOA mass balance modelling, describe how they conceptualised air pollutant interactions, and reflect on the problem-solving strategies they used during the course. These discussions provided an additional layer of assessment, capturing students' reasoning processes and their ability to transfer theoretical knowledge to applied scenarios.

Instructional Consistency and Quality Control: To ensure consistency across different lecture sections, all instructional materials, problem sets, and assessments were standardised across participating universities. Faculty members delivering the lectures followed a predefined curriculum to maintain uniformity in content delivery. Instructors participated in preparatory training sessions to align their teaching approaches with the study's research objectives, ensuring that all students received comparable exposure to mass balance modelling concepts regardless of their institution.

The validity and reliability of the assessment instruments were confirmed through expert review, with IAQ researchers and cognitive scientists evaluating the test items and problem sets to ensure alignment with the study's learning objectives. A pilot study was conducted before full implementation to refine the instructional materials and assessment procedures, identifying potential ambiguities in problem statements and ensuring that the level of mathematical complexity was appropriate for the targeted student population.

— *AI Gamified Learning Environment* —

The AI gamified learning approach was developed through a custom-built web-based interactive simulation platform designed to replicate the dynamic behaviour of SOA in indoor environments. The simulation engine incorporated a high-fidelity numerical solver capable of real-time computational modelling, integrating differential equations that govern SOA formation, transformation, and removal processes. A finite difference method (FDM) was used to solve the mass balance equations under various environmental conditions, ensuring that students could engage with real-time simulations without experiencing processing delays.

The computational framework was based on a mechanistic representation of SOA transformations, accurately reflecting real-world pollutant behaviour. The simulation accounted for ventilation, surface deposition, coagulation, filtration, and chemical transformations, allowing for a comprehensive representation of SOA dynamics. To capture the complex interaction between ozone and limonene oxidation, the model incorporated non-linear reaction kinetics, enabling students to explore the dynamic interplay between precursor emissions and secondary aerosol formation. The cloud-based nature of the simulation eliminated the need for specialised software installations, allowing students to access the platform remotely and engage with the learning experience from any location.

To ensure accuracy, empirical coefficients and reaction rate constants were derived from peer-reviewed IAQ studies. The system also incorporated a Monte Carlo uncertainty analysis module, introducing stochastic variation in environmental parameters such as fluctuating ventilation rates and non-uniform surface deposition. This feature allowed students to explore the impact of real-world variability on SOA concentration dynamics and understand the inherent uncertainties associated with indoor air quality modelling.

Interactive User Interface and Parameter Manipulation: The simulation platform provided an intuitive user interface that allowed students to manipulate key environmental parameters influencing SOA dynamics. Through interactive controls such as sliders, numerical input fields, and drop-down menus, students could adjust variables including ventilation rate, surface deposition rate, coagulation rate, filtration efficiency, and ozone-limonene reaction kinetics. The ventilation rate parameter enabled students to examine how varying air exchange rates influenced SOA dilution, while the surface deposition model allowed them to observe how different deposition rates affected air pollutant removal.

To explore particle behaviour, the simulation included a coagulation module that demonstrated how SOA particles merge to form larger clusters, altering number concentrations over time. The air filtration efficiency setting provided insights into the role of mechanical filtration in pollutant removal, allowing students to compare different filtration methods and their effectiveness in reducing SOA levels. Additionally, an embedded reaction kinetics module enabled students to visualise how changes in ozone and limonene concentrations influenced SOA formation over time.

Each parameter modification triggered an immediate update in the numerical solver, ensuring that mass balance equations, graphical outputs, and concentration profiles reflected the changes in real time. Dynamic visual feedback was provided through SOA concentration plots, air pollutant decay curves, and steady-state predictions, reinforcing the relationship between environmental conditions and SOA formation.

Progressive Learning Scaffolds and Conceptual Development: Since students had no prior knowledge of mass balance modelling, the simulation was designed with progressive learning scaffolds to facilitate structured conceptual development. Initially, students interacted with simplified models where only one or two variables were adjustable, allowing them to develop an intuitive understanding of how individual environmental factors influence SOA concentrations. These introductory simulations focused on basic pollutant removal processes, such as ventilation and filtration, ensuring that students grasped fundamental principles before progressing to more complex scenarios.

As their understanding deepened, multi-variable simulations were introduced, requiring students to apply mass balance principles across interconnected systems. The second phase integrated coagulation, deposition, and precursor oxidation, illustrating how these processes interact within an indoor environment. The final phase of the learning experience involved open-ended case studies in which students hypothesised, tested, and refined mitigation strategies to control SOA pollution under different environmental conditions. These progressively structured activities ensured that students could build confidence in their ability to model and analyse SOA dynamics effectively.

Adaptive Feedback and Real-Time Learning Adjustments: To support active learning, the simulation incorporated adaptive feedback mechanisms that responded to students' inputs in real time. Whenever a student adjusted a parameter, the system provided immediate feedback through graphical updates, explanatory text, and guided prompts that illustrated the expected impact on SOA concentrations. This feature encouraged students to engage in hypothesis-driven reasoning, ensuring that each modification was guided by theoretical principles and empirical observations rather than arbitrary trial and error.

The feedback system included error notifications that flagged unrealistic values, such as negative ventilation rates or excessively high precursor concentrations and provided corrective explanations. Predictive graphs displayed expected SOA concentration trajectories before a simulation was executed, allowing students to compare their predictions with actual results. If students struggled to achieve expected outcomes, concept reinforcement prompts provided additional explanations and recommended literature references to clarify key concepts.

To further enhance engagement, the simulation included self-assessment checkpoints where students were required to predict SOA behaviour before running a simulation. This feature encouraged active learning by compelling students to apply their conceptual knowledge before receiving computational results, reinforcing the importance of analytical reasoning and informed decision-making.

Scenario-Based Challenges and Real-World Applications: In addition to free exploration, the gamified environment included scenario-based challenges that required students to apply mass balance principles to solve realistic IAQ problems. These challenges were designed to simulate real-world decision-making, fostering problem-solving skills and critical thinking.

One challenge involved an occupant using an ozone generator while simultaneously spraying a limonene-based air freshener, prompting students to predict and mitigate the resulting SOA formation. Students had to adjust ventilation rates, modify filtration settings, and propose alternative IAQ strategies to minimise SOA accumulation. The system provided before-and-after comparisons, enabling students to evaluate the effectiveness of their mitigation strategies and refine their approaches accordingly.

Another scenario focused on a poorly ventilated indoor environment where SOA concentrations were observed to increase over time. Students were tasked with determining the most effective intervention–whether increasing ventilation and air movement, introducing air filtration, or reducing precursor emissions–based on their understanding of mass balance principles. These scenarios required students to justify their decisions using theoretical models, reinforcing their ability to connect fundamental concepts with practical applications.

The simulation also allowed students to create and test their own IAQ conditions, providing a platform for independent exploration and hypothesis testing. This feature encouraged students to extend their learning beyond predefined challenges and develop a deeper understanding of pollutant behaviour in varying indoor environments.

Real-Time Data Logging and Behavioural Analysis: The platform recorded each student's interactions in real time, capturing data on decision-making sequences, adjustment frequencies, and response times to environmental changes. These data provided valuable insights into students' engagement levels, problem-solving strategies, and learning trajectories over time. The system generated individual performance reports, highlighting areas of proficiency and identifying specific aspects where further conceptual reinforcement was needed.

By analysing interaction patterns, researchers could determine not only how much students learnt but also how they approached problem-solving. The behavioural data helped assess students' ability to apply conceptual knowledge in a dynamic setting, providing deeper insights into cognitive engagement and skill development. This data-driven approach also allowed for continuous refinement of the simulation, ensuring that the learning environment remained responsive to students' needs.

— *Data Collection* —

To measure the extent to which each instructional approach overcame cognitive barriers, the study employed a multifaceted data collection strategy integrating both quantitative and qualitative assessments. Cognitive load was assessed using the National Aeronautics and Space Administration (NASA) Task Load Index, capturing students' perceived mental effort during learning. Electroencephalography (EEG) and eye-tracking technologies were considered as supplementary measures to provide physiological evidence of cognitive engagement and mental workload.

Conceptual understanding was evaluated through structured pre-tests and post-tests comprising multiple-choice and open-ended questions designed to measure students' grasp of SOA mass balance modelling. Concept maps were used to document students' initial and post-instructional mental models, enabling an analysis of how each teaching method facilitated the development of structured and interconnected representations of SOA transformation processes.

The ability to ask the right questions, which is influenced by a combination of foundational knowledge, structured mental models, and curiosity, was assessed through written reflections and structured enquiry exercises in which students formulated research questions based on observed SOA transformations. The depth, relevance, and complexity of these questions were analysed to determine whether students had moved beyond superficial comprehension to a deeper, more inquisitive engagement with the subject matter.

Since the ability to ask meaningful questions directly influences the development of cognitive abilities such as critical and reflective thinking, abstract reasoning, logical deduction, and creative imagination, this measure provided insights into how well each instructional method supported cognitive development.

Critical and reflective thinking, abstract reasoning, logical deduction, and creative imagination were examined through problem-solving tasks in which students applied SOA mass balance concepts to propose IAQ interventions. Their responses were evaluated based on their ability to integrate theoretical principles with real-world IAQ challenges, demonstrating an understanding of how to mitigate SOA formation through ventilation strategies, air filtration, or source control. The ability to logically connect theoretical models with practical applications will be taken as a key indicator of cognitive transformation and the success of each instructional approach in fostering advanced reasoning skills.

Semi-structured interviews and focus groups provided qualitative insights into students' perceptions of their learning experiences. Discussions explored how each method influenced their confidence in engaging with complex IAQ concepts, their ability to construct logical explanations, and their inclination to approach indoor air quality issues from an evidence-based problem-solving perspective. Students' reflections on their learning process were analysed for indications of cognitive breakthroughs, shifts in mental models, and an increased ability to pose insightful research questions.

— *Data Analysis* —

Quantitative analysis involved statistical comparisons of pre-test and post-test scores to determine knowledge gains and conceptual development in both groups. Analysis of variance (ANOVA) was used to assess differences between instructional methods, while regression modelling examined the relationships between cognitive load, conceptual understanding, and the ability to formulate research questions and problem-solving strategies. Paired t-tests were conducted to evaluate within-group changes over time, providing insights into the specific cognitive developments fostered by gamified versus traditional instruction.

Concept maps were analysed using structural complexity measures, examining the number of interconnections, hierarchical depth, and accuracy of relationships between SOA transformation components. An increase in the richness and logical structure of concept maps post-instruction was indicative of cognitive growth in understanding the mass balance model.

Student-generated research questions were subjected to thematic analysis to identify patterns in curiosity development, categorising questions based on depth, specificity, and theoretical integration. Higher-order questions that demonstrated abstract reasoning, causal inference, and hypothesis formulation were taken as indicators of enhanced cognitive engagement. Since the formulation of effective questions requires a combination of foundational knowledge, structured mental models, and intellectual curiosity, this analysis was crucial for determining the extent to which each teaching approach fostered the necessary cognitive abilities for deep scientific enquiry.

Qualitative data from interviews and focus groups were transcribed and thematically analysed, focusing on students’ descriptions of how each teaching method influenced their thought processes, reasoning abilities, and overall conceptual development. Themes related to overcoming cognitive barriers, the development of logical deduction skills, and creative approaches to problem-solving were extracted to provide deeper insights into the pedagogical effectiveness of each learning method.

— *Validation and Reliability* —

To ensure the validity of cognitive assessments, test instruments underwent expert review to confirm alignment with IAQ education objectives and cognitive science principles. A pilot study was conducted to refine the gamified tool and instructional materials based on preliminary user feedback. Reliability of qualitative coding was maintained through inter-rater agreement, ensuring consistency in thematic interpretations of students’ reflections and problem-solving strategies.

4.……………………………………..

Research findings

The study revealed that AI gamification-based interactive learning environments significantly enhanced cognitive abilities and real-world problem-solving skills in IAQ education, particularly in understanding the dynamic behaviour of SOAs through mass balance modelling. Compared to traditional lecture-based instruction, students in the gamified learning group demonstrated superior conceptual understanding, problem-solving efficiency, and cognitive engagement, as evidenced by improvements in pre-test/post-test performance, conceptual mapping complexity, and enquiry-based reasoning.

— *Cognitive Load and Engagement* —

The NASA Task Load Index (NASA-TLX) results demonstrated a significant reduction in cognitive load for students in the gamified learning group compared to those receiving traditional lecture-based instruction. The overall cognitive demand was 33% lower in the gamified group, with frustration levels reduced by 48% ($p < 0.001$). Mental demand scores were lower by 21% ($p < 0.01$), reflecting how interactive simulations facilitated conceptual understanding without excessive cognitive strain.

Temporal demand was also reduced by 29% ($p < 0.01$) in the gamified group, as real-time feedback minimised the need for lengthy manual computations. Performance ratings were 39% higher ($p < 0.001$) among gamified learners, indicating a greater sense of achievement and competence in SOA mass balance modelling tasks. Effort scores were 37% lower ($p < 0.001$) in the gamified group, highlighting the reduced mental exertion required when dynamic computational tools supported learning instead of static derivations.

EEG recordings revealed pronounced differences in neural activity associated with cognitive engagement and processing efficiency. Students in the gamified learning group exhibited a 27% increase in frontal theta wave activity (4–7 Hz) compared to the traditional lecture group ($p < 0.01$), indicating enhanced cognitive engagement and problem-solving focus. Beta wave activity (13–30 Hz), typically associated with cognitive workload, was 19% lower ($p < 0.01$) in the gamified group, confirming a reduced cognitive burden.

Parietal alpha suppression (8–12 Hz) was 35% greater in the gamified group ($p < 0.001$), signifying stronger visual processing, which aligns with students' reliance on interactive simulations rather than static equations. EEG spectral entropy, a measure of cognitive flexibility, increased by 22% ($p < 0.01$) in the gamified group, indicating that students using simulations demonstrated a greater ability to adapt their reasoning strategies and integrate complex information more effectively.

Eye-tracking analysis provided additional evidence of heightened engagement in the gamified learning group. Fixation count on real-time pollutant concentration graphs was 46% higher than in the traditional lecture group ($p < 0.001$), demonstrating sustained attention on key learning elements rather than passive observation. Dwell time on parameter adjustment interfaces increased by 31% ($p < 0.01$), reflecting active engagement with ventilation, filtration, and chemical reaction variables.

Fixation dispersion was 26% lower ($p < 0.01$), indicating more concentrated visual attention and reduced cognitive drift compared to students who had to manually follow static derivations. Saccadic reaction times were 22% faster ($p < 0.05$) in the gamified group, suggesting that students were quicker in responding to dynamic environmental changes, thereby improving their ability to make real-time IAQ management decisions.

Students in the traditional lecture group exhibited signs of cognitive overload, particularly in tasks requiring multi-step mathematical manipulation without immediate computational support. High NASA-TLX effort scores aligned with increased frontal midline theta activity, reflecting sustained working memory strain.

Elevated beta-band activity in the lecture group further suggested heightened mental workload, consistent with increased time-on-task and cognitive fatigue. Eye-tracking data showed greater fixation dispersion, with students frequently shifting between lecture slides, chalkboard derivations, and personal notes, suggesting that static instruction required extensive cognitive effort to synthesise multiple sources of information.

The interactive nature of the gamified environment allowed students to intuitively adjust environmental variables and observe immediate consequences, reducing the need for prolonged mental computation. This ability to externalise problem-solving steps in a visual, interactive format led to lower reported cognitive effort, better attentional focus, and greater cognitive flexibility. EEG and eye-tracking data confirmed that gamified learning fostered a more immersive and efficient cognitive processing state, allowing students to allocate mental resources towards conceptual integration rather than equation memorisation.

The findings suggest that gamification in IAQ education not only reduces cognitive strain but also enhances problem-solving engagement by optimising attentional resources and cognitive flexibility. The ability to dynamically manipulate mass balance parameters in real time resulted in a more intuitive learning experience, enabling students to develop deeper conceptual models with reduced cognitive fatigue. These results provide strong empirical support for integrating interactive simulations in engineering education to enhance learning efficiency and engagement in complex scientific domains.

— *Conceptual Understanding and Knowledge Retention* —

The pre-test and post-test analysis demonstrated a statistically significant improvement in conceptual understanding among students who engaged with the gamified learning platform compared to those who received traditional lecture-based instruction. The gamified group exhibited a 42% increase in post-test scores, while the traditional group improved by 26% ($p < 0.01$). Pre-test scores between the two groups were statistically indistinguishable ($p = 0.67$), confirming that post-instructional differences arose from the instructional intervention rather than pre-existing disparities in knowledge.

Retention of core theoretical knowledge was significantly higher in the gamified learning group, with students demonstrating a 56% improvement in recalling SOA mass balance principles compared to a 34% improvement in the traditional group ($p < 0.01$). The ability to apply mass balance principles to real-world IAQ problems was also enhanced, with gamified learners outperforming the lecture group by 39% in solving applied problems involving SOA formation, transformation, and removal processes ($p < 0.001$). This result suggests that students in the gamified environment were not only absorbing theoretical concepts more effectively but also integrating them into practical decision-making scenarios.

Knowledge transferability was assessed through problem-solving tasks involving novel IAQ scenarios. The gamified group exhibited a 78% success rate in adapting theoretical knowledge to unfamiliar air pollutant interactions, whereas only 54% of students in the traditional group demonstrated comparable adaptability ($p < 0.001$). The ability to generalise learning to new contexts is a crucial indicator of deep conceptual understanding and cognitive flexibility, suggesting that interactive learning environments facilitate a more durable and adaptable knowledge base compared to static lecture formats.

Concept maps were used as a structural measure of students' knowledge organisation and conceptual depth before and after instruction. In the pre-test, no significant differences were observed between the two groups ($p = 0.79$), with an average of 7.2 (Standard Deviation = 2.4) concept interconnections per student across both cohorts. However, after instruction, the gamified group exhibited a 92% increase in conceptual interconnections (Mean = 13.8, SD = 3.1), compared to a 45% increase in the traditional lecture group (M = 10.4, SD = 2.9) ($p < 0.001$).

Post-test concept maps from the gamified group revealed a higher degree of hierarchical complexity, with students demonstrating a more sophisticated understanding of the relationships between SOA transformation mechanisms, including ventilation rate, deposition processes, coagulation dynamics, air filtration efficiency, and ozone-limonene reaction kinetics. The logical coherence of concept maps improved by 67% in the gamified group, compared to 34% in the traditional lecture group ($p < 0.001$).

The structure of concept maps from gamified learners more closely resembled expert-level representations, suggesting that interactive simulations facilitated a shift from linear memorisation of mass balance equations to systems-based reasoning about IAQ dynamics. Gamified students were more likely to include causal feedback loops, indicating a deeper understanding of non-linear pollutant interactions in indoor environments. This suggests that the gamified approach reinforced holistic knowledge construction, rather than reliance on static procedural formulae.

A delayed retention test administered four weeks post-instruction revealed significant differences in knowledge retention. Students in the gamified learning group retained 78% of their post-test conceptual knowledge, whereas the traditional lecture group retained only 52% ($p < 0.001$). When presented with unfamiliar SOA modelling challenges requiring the application of mass balance principles to novel scenarios, the gamified group demonstrated a 61% higher problem-solving success rate than the traditional group ($p < 0.001$).

Analysis of longitudinal knowledge retention patterns suggests that the interactive, problem-solving nature of gamified learning leads to stronger conceptual encoding, reducing the typical decay in memory observed in traditional instruction. The gamified students were more likely to retain and apply their learning across extended periods, reinforcing the idea that experiential, simulation-based learning enhances the long-term durability of knowledge.

Several key cognitive mechanisms explain the superior performance of the gamified group in conceptual understanding, knowledge retention, and real-world problem-solving. The platform's integration of visual, textual, and interactive computational elements facilitated multi-sensory encoding, strengthening both verbal and non-verbal memory traces. This redundancy in encoding pathways enhanced recall and conceptual integration, making students more adept at applying mass balance principles to unfamiliar IAQ scenarios.

The interactive simulation reduced extraneous cognitive load, allowing students to allocate more working memory resources towards schema construction and conceptual synthesis, as evidenced by lower NASA-TLX cognitive strain scores. In contrast, traditional instruction imposed a higher intrinsic cognitive load, leading to greater mental effort in processing static mathematical derivations without visual or interactive reinforcement.

The real-time nature of gamified learning enabled students to actively test assumptions, adjust environmental parameters, and refine their conceptual models iteratively. The ability to observe immediate cause-and-effect relationships reinforced deeper learning compared to static, lecture-based instruction, where feedback was often delayed or absent.

The gamified group engaged in frequent iterative problem-solving cycles, requiring continuous retrieval and application of knowledge. Research in cognitive science suggests that retrieval-based learning enhances memory consolidation, explaining the superior retention rates in the gamified group compared to passive lecture-based learners.

The findings provide strong empirical evidence that AI gamification-based interactive learning environments significantly outperform traditional lecture-based instruction in fostering conceptual understanding, long-term knowledge retention, and real-world knowledge application. Students who engaged in real-time pollutant modelling, interactive scenario testing, and adaptive feedback loops not only demonstrated stronger problem-solving skills but also retained their conceptual understanding over extended periods, enabling them to apply theoretical principles in novel IAQ management contexts.

The ability to manipulate environmental parameters, visualise real-time SOA formation, and receive immediate computational feedback proved to be a transformative factor in bridging the gap between theoretical knowledge and applied IAQ decision-making. Given these results, integrating gamified simulations into engineering curricula offers a scalable, effective solution for enhancing conceptual learning in complex environmental science domains.

— *The Role of Gamification in Enabling Students to Ask the Right Questions* —

One of the most striking findings was the significant improvement in students' ability to ask meaningful, scientifically relevant questions, which directly influenced their development of critical and reflective thinking, abstract reasoning, logical deduction, and creative imagination. The ability to pose insightful scientific questions is foundational to intellectual enquiry, serving as a direct reflection of cognitive engagement, conceptual understanding, and knowledge integration. The enquiry assessment conducted before and after instruction revealed profound differences in students’ questioning abilities, particularly in the gamified learning group, where students exhibited a substantial shift from fact-based, surface-level queries to complex, systems-based scientific enquiries.

In the pre-test enquiry assessment, students in both the traditional and gamified groups primarily asked basic, descriptive, and factual questions, indicative of a low level of cognitive engagement and minimal conceptual integration. The vast majority of pre-instruction questions fell within the lower-order categories of Bloom’s Taxonomy, emphasising simple knowledge recall and fundamental comprehension rather than critical analysis or synthesis. Typical pre-test questions included, “What is an SOA?”, “What happens when ozone reacts with limonene?”, and “How does an air filter remove pollutants?”.

These questions, while demonstrating some awareness of the core topics, lacked any indication of deeper reasoning, hypothesis generation, or problem-solving intent. The structural analysis of pre-test questions across both groups showed that 82% of student-generated enquiries were single-variable, fact-seeking questions, with no exploration of interactions between different parameters governing SOA behaviour.

The post-instruction enquiry assessment revealed a highly significant shift in the complexity and structure of student-generated questions, particularly among students who participated in the gamified learning experience. Instead of simply seeking definitions or mechanistic descriptions, students in the gamified group posed highly integrative, hypothesis-driven, and multi-variable questions, demonstrating a deeper conceptual understanding, enhanced curiosity, and improved cognitive flexibility.

Representative questions included, “How does altering ventilation rate interact with coagulation and deposition processes to influence SOA dynamics in a real indoor setting?”, “What non-linear effects might emerge when precursor emissions vary with occupant activity levels?”, and “Could different surface materials influence SOA deposition rates, and how might these effects be mitigated in energy-efficient buildings?”.

These questions reflect a major cognitive transition from simple recall to complex, predictive, and systems-based thinking. The shift in enquiry structure was statistically significant, with a 73% increase in multi-variable question formulations in the gamified group compared to only a 29% increase in the traditional lecture group ($p < 0.001$).

Linguistic and structural analysis of post-instruction questions confirmed the elevated conceptual complexity in the gamified learning group. Lexical density analysis indicated that post-test questions from the gamified group contained 36% more technical, process-oriented, and model-based terms than those from the traditional lecture cohort. Enquiry progression metrics revealed that students in the gamified environment were significantly more likely to ask exploratory, counterfactual, and model-based questions, suggesting a deeper engagement with predictive reasoning and scientific modelling.

Network graph analysis of student-generated questions further revealed that the semantic structure of post-instruction enquiries was significantly more interconnected, hypothesis-driven, and systemically structured in the gamified group than in the lecture-based group, indicating a major advancement in students' ability to frame scientific problems within a multi-variable context.

The cognitive mechanisms underpinning this transformation in questioning ability can be attributed to three key factors facilitated by the gamified learning environment: dynamic real-time interaction, adaptive feedback, and experiential problem-solving cycles. First, the interactive nature of the gamified simulation allowed students to manipulate environmental parameters and observe their effects on SOA concentrations in real time, reinforcing a hypothesis-driven learning process.

Instead of passively receiving knowledge, students actively tested variables, observed emergent behaviour, and formulated new questions based on real-time computational feedback. This form of experiential learning aligns with constructivist cognitive models, which emphasise that knowledge is best developed through active engagement and iterative refinement.

Second, adaptive feedback loops within the gamified platform played a critical role in fostering deeper enquiry. Unlike traditional lecture-based learning, where feedback is often delayed or indirect, the gamified simulation provided instantaneous feedback on parameter adjustments, prompting students to ask higher-order exploratory questions. Students who observed unexpected changes in pollutant concentrations were naturally encouraged to investigate causal mechanisms, interactions between variables, and real-world applicability of mass balance principles, reinforcing scientific curiosity and structured reasoning.

Third, the immersive problem-solving cycles embedded within the gamified environment encouraged students to engage in predictive reasoning, scenario testing, and model-based decision-making. By working through realistic IAQ challenges–such as determining the optimal filtration strategy to mitigate SOA accumulation or predicting the compounding effects of varying precursor emissions and ventilation rates–students developed a more intuitive and systemic understanding of pollutant dynamics.

This active problem-solving approach strengthened critical and reflective thinking, logical deduction, and creative imagination, as students were required to synthesise information across multiple domains, test alternative hypotheses, and refine their reasoning iteratively.

Comparative analysis of the traditional lecture-based cohort showed a slower and less pronounced shift from fact-based to conceptual enquiry. While students in the lecture-based group exhibited some improvement in question complexity, their post-test questions remained largely single-variable and mechanistic, lacking the multi-variable interactions and systems-based reasoning observed in the gamified group.

Enquiry pattern analysis showed that only 41% of post-instruction questions in the lecture group contained hypothesis-driven components, compared to 82% in the gamified group ($p < 0.001$). The absence of interactive feedback mechanisms and real-time variable manipulation likely constrained students' ability to explore emergent pollutant behaviour dynamically, resulting in a more linear and less exploratory approach to scientific enquiry.

The ability to pose meaningful scientific questions is a fundamental driver of intellectual and cognitive growth, serving as the foundation for advanced reasoning, innovation, and problem-solving. The findings of this study provide compelling evidence that gamification fosters deeper scientific curiosity, enhances structured reasoning, and develops the cognitive abilities necessary for systems-based problem-solving.

The ability to manipulate environmental parameters in real time, visualise complex interactions, and receive immediate feedback empowered students to formulate sophisticated scientific enquiries, significantly advancing their critical and reflective thinking, abstract reasoning, logical deduction, and creative imagination.

These findings underscore the transformative potential of gamified learning environments in STEM education, particularly in disciplines where multi-variable interactions and dynamic systems modelling are critical for problem-solving.

— *Development of Cognitive Abilities* —

Students in the gamified learning group exhibited significant improvements in logical deduction and abstract reasoning when solving IAQ-related case studies, with measurable enhancements in their ability to identify causal relationships between environmental parameters and pollutant behaviour.

The ability to integrate multiple variables, predict non-linear air pollutant transformations, and apply theoretical knowledge to real-world IAQ scenarios was notably stronger among students who engaged in interactive simulations compared to those in the lecture-based group. These improvements were observed through decision-making speed, accuracy, and adaptability during problem-solving sessions, highlighting the cognitive advantages of gamified learning in fostering advanced reasoning skills necessary for expert-level IAQ management.

Critical and reflective thinking were significantly more developed in the gamified group, as demonstrated by self-evaluations and post-simulation reflections that showed a higher tendency to critique decision-making processes, adjust strategies, and explore alternative IAQ mitigation approaches. Post-intervention analysis revealed that 83% of gamified learners revised their initial pollutant control strategies after receiving real-time feedback from the simulation, compared to 49% in the traditional lecture group ($p < 0.001$).

This active engagement in reassessing and refining problem-solving approaches was indicative of a strong critical thinking ability, as students were required to identify flaws in their initial assumptions, recognise gaps in their understanding, and develop more effective intervention strategies based on observed data. The ability to question the reliability of their models, consider additional environmental factors, and explore alternative interpretations of pollutant behaviour further reinforced their reflective thinking capabilities.

Unlike students in the lecture-based group, who primarily focused on deriving solutions from predefined equations, gamified learners were more likely to engage in higher-order metacognitive strategies, such as evaluating the limitations of their assumptions, discussing competing IAQ mitigation strategies, and testing multiple pollutant control scenarios. This demonstrated a shift from static knowledge application to dynamic, iterative learning, fostering a deeper ability to apply scientific reasoning in IAQ management.

Abstract reasoning improvements were evident in students' ability to connect theoretical mass balance models to complex, real-world IAQ scenarios, a skill that was significantly stronger in the gamified group. When tasked with predicting SOA formation under varying precursor emission levels, 72% of gamified learners successfully transferred their theoretical knowledge to novel case studies, compared to only 46% of students in the traditional lecture group ($p < 0.001$).

This ability to generalise mass balance principles beyond textbook examples was further reinforced by post-simulation assessments, in which gamified learners demonstrated a 61% increase in their ability to formulate conceptual models linking SOA formation, ventilation, and chemical transformations to broader IAQ management strategies. The interactive nature of the simulation enabled students to explore real-time cause-and-effect relationships, fostering deeper conceptual understanding and eliminating misconceptions that often arise from purely theoretical instruction.

Logical deduction was particularly enhanced among gamified learners, as reflected in their superior multi-variable problem-solving accuracy when predicting pollutant behaviour under dynamic environmental conditions. Students in the gamified group outperformed their lecture-based peers in scenario-based IAQ modelling tasks, with a 42% higher accuracy rate in predicting changes in SOA concentrations in response to ventilation, filtration, and chemical reaction rate adjustments ($p < 0.001$).

The ability to recognise interdependencies between different mass balance components, such as the combined effects of ventilation rate, surface deposition, and coagulation on SOA dynamics, was significantly higher in the gamified group. EEG data collected during decision-making tasks further confirmed increased frontal theta activity, associated with logical reasoning and cognitive processing efficiency, in students using the interactive simulation compared to those relying on static, lecture-based instruction.

The dynamic nature of the simulation allowed students to iteratively test hypotheses, observe pollutant transformations in real time, and refine their decision-making strategies, resulting in faster response times and higher predictive accuracy in pollutant behaviour assessments.

Creative imagination flourished in the gamified learning environment, with students demonstrating a greater propensity for hypothesis-driven exploration and innovative IAQ solutions. When prompted to design an IAQ intervention for a high-occupancy indoor space with poor ventilation and high precursor emissions, gamified learners proposed 67% more novel mitigation strategies than their lecture-based peers, incorporating hybrid filtration-ventilation approaches, air pollutant sequestration methods, and real-time adaptive control systems.

One of the most innovative proposals included a dynamic IAQ control system integrating real-time sensor feedback with an AI-driven IAQ management algorithm, capable of adjusting ventilation and filtration settings based on fluctuating SOA concentrations. Such imaginative problem-solving approaches suggest that gamification does not merely enhance retention of IAQ knowledge but actively fosters creative thinking, pushing students towards innovative, real-world applications of environmental engineering principles.

The collective findings confirm that gamification in IAQ education extends beyond improving factual recall to cultivating the higher-order cognitive skills necessary for expert-level problem-solving. The ability to dynamically interact with environmental variables, test alternative pollutant mitigation strategies, and receive immediate feedback on decision-making outcomes significantly enhanced students' cognitive flexibility, adaptability, and real-world problem-solving capabilities.

By bridging the gap between theoretical mass balance modelling and applied IAQ management, gamification prepares students to think critically and reflectively, reason abstractly and logically, and develop innovative solutions through creative imagination to emerging environmental challenges, positioning it as a superior pedagogical tool for training the next generation of IAQ professionals and environmental engineers.

— Comparative Performance in Scenario-Based IAQ Decision-Making —

During real-world scenario testing, students in the gamified learning group demonstrated superior accuracy in optimising IAQ conditions while maintaining other key indoor environmental quality (IEQ) parameters, including thermal comfort, acoustic conditions, and energy efficiency. The ability to simultaneously manage multiple constraints in a dynamic environment was significantly more developed among gamified learners compared to those in the traditional lecture-based instruction group.

The gamified group achieved an 87% success rate in optimising IAQ without compromising other IEQ parameters, whereas the traditional group achieved only 64% ($p < 0.001$). The significant disparity in performance highlights the cognitive advantages of interactive, real-time learning environments, where students actively experiment with trade-offs rather than relying on static, theoretical models.

One of the primary challenges in real-world IAQ management is the integration of multi-variable constraints, where improving one environmental parameter often impacts another. Traditional instruction, which focuses primarily on IAQ parameters in isolation, left students ill-equipped to balance competing environmental factors effectively. During testing, participants from the lecture-based group often over-prioritised IAQ interventions at the expense of thermal comfort and energy efficiency, leading to suboptimal solutions such as excessive ventilation, which compromised temperature stability and increased HVAC energy consumption.

In contrast, gamified learners demonstrated significantly greater adaptability, adjusting ventilation rates, air filtration settings, and chemical precursor controls with a deeper understanding of their interdependencies. The ability to experiment within an interactive simulation allowed them to test multiple strategies in real time, recognise the compounding effects of different IAQ interventions, and optimise their decision-making based on predictive modelling feedback.

The improved decision-making adaptability in the gamified learning group was evident in how students approached complex trade-offs between pollutant removal efficiency, thermal regulation, and acoustic comfort. When confronted with a high-occupancy environment where CO_2 accumulation was rising alongside SOA formation, traditional learners predominantly responded by increasing ventilation rates, often exceeding recommended airflow thresholds and inadvertently causing discomfort due to increased draughts and temperature fluctuations.

In contrast, gamified learners applied a more strategic approach, recognising that an optimal solution required modulating filtration efficiency and localised source control rather than relying solely on ventilation adjustments. They incorporated active monitoring of precursor emissions and fine-tuned their filtration strategies, achieving IAQ improvements with minimal disruption to thermal equilibrium.

Real-time feedback and interactive scenario testing significantly enhanced the gamified group's capacity to predict non-linear responses in IAQ management. Students in this group exhibited faster reaction times and higher accuracy in modifying environmental parameters based on changing indoor conditions. Eye-tracking and EEG data indicated greater sustained attention to real-time variable changes in the gamified group, correlating with higher cognitive processing activity in regions associated with complex decision-making and adaptive learning.

When tasked with mitigating ozone-induced SOA formation while ensuring energy efficiency, gamified learners experimented with a combination of moderate ventilation adjustments and enhanced filtration settings, preventing unnecessary energy expenditure while effectively controlling airborne pollutants. In contrast, students in the traditional instruction group tended to rely on rigid, pre-learned formulae, often overlooking more nuanced control strategies such as variable air volume (VAV) system adjustments and zone-based air distribution methods.

Another key distinction between the two groups was their capacity for real-time performance refinement. Gamified learners iteratively tested, assessed, and refined their IAQ strategies based on real-time feedback, leading to a measurable improvement in their ability to optimise environmental conditions dynamically.

By contrast, traditional learners were less flexible in their decision-making, struggling to modify their approach when initial strategies failed to yield optimal results. Performance logs from the gamified platform revealed that students in this group made 68% more iterative parameter adjustments before finalising their IAQ strategies, whereas students in the lecture-based group made significantly fewer refinements, often committing prematurely to suboptimal solutions.

The ability to navigate complex, interdependent environmental conditions is critical in real-world IAQ management, where achieving optimal air quality often necessitates balancing multiple competing factors. The results of this study provide strong empirical evidence that interactive, simulation-based learning environments significantly enhance problem-solving skills and decision-making agility compared to traditional instruction.

The gamified approach not only improved students' understanding of IAQ principles but also enhanced their ability to apply that knowledge within the broader framework of holistic indoor environmental quality management. These findings underscore the practical applicability of gamification in training future IAQ professionals, ensuring they are equipped to develop effective, energy-efficient, and occupant-friendly air quality solutions in real-world environments.

— *Challenges and Limitations* —

Despite its effectiveness, AI gamification-based learning presented several challenges that required careful mitigation strategies to ensure optimal student engagement and cognitive development. One of the primary difficulties was the initial struggle with the interactive interface, particularly among students with limited prior exposure to digital learning tools or computational simulations. Some students required longer onboarding times than anticipated to navigate the platform effectively, slowing their initial engagement with the problem-solving tasks.

Interface usability metrics indicated that 21% of students in the gamified group experienced difficulty understanding the system's controls and parameter adjustments during the first week of instruction. Eye-tracking data revealed higher fixation durations and increased cognitive load scores in these students, indicating a period of adaptation where they needed to process both the interface mechanics and the underlying IAQ concepts simultaneously.

Another significant challenge stemmed from the open-ended nature of problem-solving scenarios, which introduced cognitive uncertainty that some students found overwhelming. Unlike traditional instructional methods, where problem-solving steps are explicitly outlined, gamification encouraged exploratory learning, requiring students to formulate their own hypotheses, test different mitigation strategies, and refine their approach based on real-time feedback.

For students accustomed to highly structured learning environments, this shift initially caused decision paralysis and uncertainty in strategy selection. Survey responses indicated that 38% of students in the gamified group felt unsure about which air pollutant mitigation strategy to test first, while 26% reported difficulty in identifying the most critical environmental variables influencing IAQ outcomes.

To address these challenges, progressive learning scaffolds were implemented to gradually introduce complexity, allowing students to build confidence in their analytical abilities over time. The learning platform was structured into tiered difficulty levels, where students first engaged with simplified, guided scenarios focusing on single-variable adjustments before progressing to multi-variable, real-world IAQ management tasks.

This phased approach reduced cognitive overload, ensuring that students internalised foundational principles before encountering more complex problem-solving challenges. Adaptive feedback mechanisms further supported students by providing contextual hints, automated explanations, and suggested next steps when they struggled with a particular scenario.

By the third week of instruction, 85% of initially overwhelmed students reported improved confidence in their ability to navigate the simulation and solve IAQ-related problems effectively. Post-intervention assessments showed that students who initially struggled exhibited comparable conceptual understanding and problem-solving performance to their peers, demonstrating that learning scaffolds effectively mitigated onboarding difficulties and cognitive uncertainty while preserving the advantages of exploratory, gamified learning.

— *Conclusion and Implications for IAQ Education* —

The findings of this study provide strong empirical evidence supporting the integration of AI gamification-based interactive learning environments in indoor air quality (IAQ) education, particularly for teaching mass balance modelling of SOA. The data demonstrate that gamification enhances conceptual understanding, fosters deep scientific enquiry, and strengthens the cognitive abilities necessary for real-world IAQ problem-solving.

Compared to traditional lecture-based instruction, students in the gamified learning group exhibited higher accuracy in multi-variable pollutant modelling, greater retention of theoretical concepts, and superior adaptability in applied IAQ scenarios. These results underscore the transformative impact of interactive, feedback-driven learning environments in environmental engineering education.

One of the most profound impacts of gamification was its ability to enhance conceptual understanding by enabling students to directly manipulate environmental variables, observe emergent SOA behaviours, and test pollutant control strategies in real time. The gamified approach bridged the gap between theoretical equations and real-world air quality management, ensuring that students internalised mass balance principles rather than merely memorising them.

This advantage was reflected in post-test assessments, where gamified learners outperformed traditional students by 42% in conceptual understanding and by 61% in problem-solving accuracy in complex IAQ scenarios. Concept mapping analysis further confirmed that gamified students developed more structured, interconnected, and hierarchically complex representations of SOA formation and removal processes, demonstrating a higher level of cognitive integration and systemic reasoning.

The study also revealed a significant enhancement in students’ ability to ask meaningful scientific questions, an essential skill for scientific enquiry and critical reasoning. The pre-test enquiry assessment showed that students in both instructional groups primarily posed fact-based, single-variable questions, indicating limited mental modelling and superficial reasoning. However, post-instruction analysis revealed that gamified learners exhibited a 73% increase in hypothesis-driven, multi-variable enquiries, compared to 29% in the traditional group ($p < 0.001$).

Students in the gamified cohort were significantly more likely to explore causal relationships between IAQ parameters, predict non-linear pollutant transformations, and propose alternative mitigation strategies, demonstrating a more sophisticated and exploratory approach to scientific reasoning.

These cognitive gains were closely linked to the ability of gamification to address cognitive barriers stemming from a lack of foundational knowledge, mental models, and curiosity. Traditional lecture-based methods often assume pre-existing conceptual frameworks, leading to cognitive overload when students lack prior exposure to mass balance modelling.

In contrast, gamified simulations provided progressive scaffolding, ensuring that students built fundamental conceptual models before tackling more complex IAQ problems. The interactive platform's adaptive feedback mechanisms, real-time data visualisation, and scenario-based challenges encouraged students to iteratively refine their understanding, fostering deep cognitive engagement.

By strengthening critical and reflective thinking, abstract reasoning, logical deduction, and creative imagination, gamification enabled students to develop expert-level IAQ management strategies, ensuring that theoretical knowledge was seamlessly transferred to real-world applications.

Post-simulation self-assessments showed that 83% of gamified learners revised their initial pollutant control strategies after receiving real-time feedback, compared to 49% in the traditional instruction group. This iterative learning process closely mirrors real-world IAQ decision-making, reinforcing the practical applicability of gamified learning environments in professional training for environmental engineers, IAQ specialists, and sustainability consultants.

The study's empirical findings present a compelling case for educational institutions to integrate AI gamification-based learning tools into IAQ curricula, ensuring that future professionals acquire both theoretical expertise and the cognitive flexibility required for real-world problem-solving.

By aligning IAQ education with interactive, enquiry-driven pedagogical approaches, academic institutions can equip students with the analytical skills needed to tackle complex, multi-variable IAQ challenges in diverse built environments. The results of this research highlight a paradigm shift in engineering education, demonstrating that gamified learning is not merely an enhancement but a necessity for cultivating the next generation of environmental scientists and IAQ professionals.

5……………………………………..

Fresh from his PhD, where he had pioneered the idea of AI-driven gamification for IAQ education, Adebanjo secured a highly prestigious postdoctoral fellowship at the Institute for Sustainable Environments and Intelligent Learning Technologies at Whitehouse University. This was no ordinary postdoc position. It was a launching pad–an opportunity to refine his ideas, expand his methodologies, and, most significantly, advance the integration of AI into gamification-based learning environments in ways that had not been possible during his PhD research.

His postdoctoral research coincided with a period of rapid advancements in AI, particularly in machine learning, adaptive simulations, and real-time cognitive feedback systems. These technological breakthroughs presented unprecedented opportunities for transforming how IAQ education was approached. The convergence of his work with these AI developments propelled his research forward at an extraordinary pace, allowing him to explore more sophisticated, intelligent, and immersive learning environments than he had ever envisioned.

His early postdoctoral work was unconventional, bordering on radical. While many researchers in IAQ remained fixated on traditional engineering solutions–better filtration systems, improved ventilation strategies, and air pollutant mitigation–Adebanjo saw a deeper, more fundamental issue. The real problem was not just the air people breathed; it was the way they thought about air quality. The real challenge lay in how professionals and students conceptualised IAQ issues and approached problem-solving in the field.

He had long believed that solving IAQ problems required more than just better answers–it required teaching people how to ask better questions. The limitations in IAQ management were cognitive as much as they were technical. Policymakers made reactive decisions. Engineers designed solutions without fully considering their systemic impacts. Industry professionals relied on outdated, one-dimensional approaches to ventilation and air cleaning. The field needed a fundamental shift in thinking, and Adebanjo believed that AI-enhanced gamification was the key to unlocking that transformation.

During his PhD, he had laid the foundation for gamification-based learning in IAQ education, but it was during his postdoctoral research that AI became a transformative element. The rapid advancements in deep learning, natural language processing, and real-time simulation engines enabled him to develop intelligent learning environments that adapted dynamically to users' thought processes and decision-making patterns. This shift elevated his work from an experimental learning tool to a revolutionary cognitive development platform.

His proposal, however, was met with scepticism. The academic community, steeped in decades of conventional IAQ research, was hesitant to embrace something that sounded more like a video game than a serious scientific approach. Yet, Adebanjo had never been one to accept the status quo. He had spent his life challenging assumptions, and this was no different.

Determined to prove his ideas, he threw himself into his research, collaborating across disciplines to develop AI-driven interactive learning environments that would fundamentally alter how IAQ was taught, studied, and applied. His simulations did not just teach concepts; they immersed users in real-world IAQ crises, allowing them to manipulate environmental variables, predict pollutant behaviour, and test mitigation strategies in dynamic, evolving virtual environments.

As AI technologies continued to evolve at an extraordinary pace, Adebanjo's research benefited immensely. The increasing sophistication of AI-powered decision-support systems, reinforcement learning algorithms, and adaptive educational models made it possible to create truly immersive and intelligent learning experiences. His simulations were no longer just digital tools; they became personalised learning assistants, capable of understanding a user's cognitive strengths and weaknesses and tailoring challenges accordingly.

As his research progressed, his findings became impossible to ignore. Students and professionals who engaged with AI-enhanced gamification demonstrated significantly stronger cognitive flexibility, higher problem-solving accuracy, and a more effective ability to apply IAQ management strategies in real-world scenarios. They did not just memorise principles; they learned to think like engineers–to anticipate challenges, analyse complex systems, and create innovative solutions tailored to specific environmental contexts.

Adebanjo's work attracted international attention. Universities began integrating his methodologies into their IAQ and environmental engineering curricula. Industry leaders sought his expertise in applying AI-driven cognitive learning to corporate sustainability programs. Policymakers, recognising the potential of his research, started exploring how AI-enhanced education could shape regulations and building codes to ensure healthier indoor environments.

The alignment of Adebanjo's research career with AI's rapid evolution was more than just fortunate timing–it was a perfect synergy of scientific inquiry and technological progress. The AI-driven gamification that had begun as a bold idea in his PhD had now become a transformative force in IAQ education and practice–one that was shaping the future of learning, policy, and environmental health worldwide.

By the time his fellowship ended, Adebanjo was no longer just a promising researcher. He was leading a movement. His PhD and postdoctoral research had demonstrated something profound–that cognitive transformation through AI and gamification was not just a theoretical possibility but an actionable, scalable approach to solving real-world IAQ challenges.

Adebanjo Kareem's rise to Assistant Professor at Whitehouse University was not just another step in an academic career–it was the moment his research took on an entirely new life. His PhD and postdoctoral works had laid the foundation, proving that AI-driven gamification could transform how students and professionals engaged with IAQ concepts. But now, he had a chance to move beyond the lab, beyond controlled experiments, and into the real world.

Whitehouse University saw him not just as an exceptional researcher but as a visionary, someone who could redefine the intersection of IAQ management, AI, and cognitive engineering. At only thirty-two, he became one of the youngest faculty members in his department, a recognition of his unparalleled contributions.

Despite the prestige of his new position, Adebanjo was not interested in titles or accolades. He had only one goal: to change the way people learnt, thought, and applied IAQ knowledge. He understood that real transformation was not just about publishing papers–it was about building something enduring, something that could outlive his tenure in academia.

He wasted no time. With major funding from industry leaders and government-backed AI research initiatives, he founded the Cognitive Engineering and IAQ Innovation Lab–a groundbreaking research hub where AI, gamification, and engineering education converged to train the next generation of problem-solvers.

This lab was not just a theoretical playground for PhD students. It became a nerve centre for transforming IAQ education and professional training. Here, students, industry professionals, and policymakers were no longer memorising IAQ concepts. Instead, they were stepping into AI-driven immersive learning environments, where real-time IAQ simulations challenged them to solve indoor air quality crises, design sustainable indoor environments, and predict the behaviour of pollutants in dynamic, real-world conditions.

Adebanjo’s classrooms were unlike anything seen before. The lecture hall was obsolete, replaced by an interactive, problem-solving laboratory. Students were no longer passive recipients of knowledge; they became engineers in the making, tackling complex IAQ scenarios in real time.

His first-year students, typically overwhelmed by the mathematical complexity of IAQ modelling, suddenly found themselves excited by the challenge. They were not just plugging numbers into equations; they were watching those equations come to life. They could manipulate ventilation rates, adjust pollutant sources, and see in real time how these changes affected indoor air quality. For the first time, IAQ was not an abstract science–it was tangible, interactive, and deeply engaging.

The impact was immediate. Students who once struggled with the cognitive barriers of IAQ education now demonstrated greater analytical reasoning, higher problem-solving accuracy, and stronger interdisciplinary thinking. However, Adebanjo was not satisfied with transforming just his students. He saw the potential of his methods far beyond the university walls.

Industries quickly took notice. As IAQ technology firms recognised the need to enhance workforce competency and engagement in solving IAQ challenges, they sought innovative ways to integrate AI-enhanced gamification to corporate training programmes. These gamification platforms, inspired by Adebanjo’s pioneering work, transformed IAQ education from static learning into an immersive, interactive experience.

The platforms leveraged advanced artificial intelligence to create dynamic, real-time simulations of various IAQ scenarios, allowing users to interact with virtual environments that mirrored real-world complexities. Professionals could manipulate ventilation rates, adjust air filtration strategies, and monitor pollutant dispersion in high-fidelity digital twins of buildings. AI-driven scenario generators introduced unpredictable challenges—such as sudden outdoor pollution spikes, unexpected HVAC failures, or occupant behaviour variations—forcing users to adapt and refine their IAQ management strategies under realistic constraints.

Additionally, these platforms incorporated adaptive learning algorithms that analysed user performance, tailoring difficulty levels and feedback to individual progress. Professionals received instant insights into the consequences of their decisions, enabling iterative learning and deeper understanding. Some firms even integrated wearable VR technology, further immersing trainees in virtual building environments where they could ‘walk through’ rooms, assess air quality conditions, and make real-time adjustments using voice or gesture commands.

By fostering critical thinking and decision-making skills in a risk-free digital space, these AI-enhanced gamification platforms ensured that IAQ professionals developed a more intuitive grasp of complex IAQ interactions before applying their knowledge in real-world settings. The widespread adoption of these platforms across major IAQ firms demonstrated the transformative impact of Adebanjo's work in reshaping industry training methodologies.

The IAQ sector had long been plagued by rigid, outdated training programmes, where professionals learnt through static textbooks and uninspiring workshops. But Adebanjo's AI-enhanced gamification models provided an entirely new way to train architects, engineers, facility managers, and environmental consultants.

Corporate sustainability teams began integrating his cognitive learning methodologies into employee training programmes. Large real estate firms adopted his AI-powered systems to train facility managers on proactive IAQ management, ensuring healthy indoor air and environmental quality delivery in commercial and residential buildings.

Before long, his work was not just influencing students but actively reshaping IAQ industry practices. For Adebanjo, this was the true measure of success–not just publishing research but seeing his work transform how IAQ was managed at every level, from policy to practice. But this was only the beginning.

Adebanjo's ground breaking research, coupled with his unprecedented publication record, propelled him to early tenure and a promotion to Associate Professor. His influence now extended beyond academia, into global policymaking, industry best practices, and AI-driven sustainability strategies.

His methodologies became the gold standard in IAQ education, integrated into smart building design protocols, IAQ monitoring and control systems, and public health strategies for respiratory disease prevention.

He was invited to co-author global policy frameworks on how AI-driven cognitive learning could revolutionise environmental health and sustainable building engineering. His insights reshaped the way cities approached indoor air regulation, ensuring that IAQ management was no longer just about meeting minimum compliance standards but about implementing intelligent, predictive, and proactive solutions.

His ground breaking book, Thinking Air: How AI and Gamification Are Transforming IAQ and Sustainable Building Engineering, became an international bestseller, influencing policymakers, educators, and industry leaders. It became required reading in IAQ certification programmes and environmental engineering courses worldwide.

IAQ was no longer a field governed by rigid, reactionary solutions. It had evolved into a forward-thinking discipline, guided by AI-powered cognitive learning, thanks to Adebanjo's vision.

By his mid-forties, Adebanjo had ascended to Full Professor, becoming a world-leading authority on cognitive transformation in engineering education, AI-enhanced problem-solving, and sustainable IAQ management. His AI-powered cognitive augmentation systems became industry-standard tools, ensuring that professionals could predict, analyse, and resolve IAQ challenges before they escalated.

His methodologies reduced respiratory-related hospital admissions, improved public health, and ensured that data-driven IAQ management was not just an academic pursuit but a real-world necessity. However, his greatest achievement lay in the transformation of minds. He had begun his journey believing his purpose was to fix IAQ problems, yet, in the end, he had done much more. He had engineered intelligence itself, equipping thousands of professionals, researchers, and students with the ability to ask the right questions, think critically, reflectively, logically, abstractly, and innovate effectively. Adebanjo Kareem had not only solved IAQ challenges–he had redefined the future of knowledge itself.

Adebanjo Kareem's personal transformation was as profound as his professional success. The struggles that had once defined his childhood–the relentless battle for breath, the silent sacrifices of his parents, the weight of limitations imposed by circumstances–had gradually faded into the background, replaced by a life of security, comfort, and fulfilment.

The boy who had once clutched his inhaler as a lifeline now lived in a world where clean air was not a privilege but a certainty. His journey had led him to reshape IAQ education, revolutionise cognitive learning, and influence sustainable building engineering, yet his greatest reward was not found in accolades or institutional recognition. It was in the life he was now able to give his family, a life free from the very burdens that had once seemed inescapable.

His father had long retired from the gruelling construction labour that once consumed his youth, no longer enduring the relentless sun and the punishing demands of a foreign land. For years, he had turned to plumbing and sanitary repair work, keeping himself occupied with tasks that were far less strenuous but still demanding. Yet, even as his hands remained busy, the weight of financial uncertainty had never truly lifted–until now.

Adebanjo had built a future where his father no longer needed to work out of necessity but could choose to engage only in what brought him a sense of purpose and fulfilment. Now, he sat in the home his son had bought–a home where clean air flowed freely, where every element was carefully considered to promote health and comfort, ensuring that his father's later years were spent in an environment designed not just for survival, but for true well-being. It was a space that reflected Adebanjo's gratitude, a home where his father could finally rest without worry, knowing that the sacrifices of his past had paved the way for a life of security and peace.

His mother, who had spent her life stretching every coin, rationing every meal, and sacrificing every comfort for the sake of her only child, now lived with a sense of ease she had never known. No longer burdened by the relentless worries of survival, she shared a home with Adebanjo's father (her husband) where she could finally rest without the weight of past struggles pressing upon her. The silent suffering she had endured for years had not been forgotten by her son.

Adebanjo had ensured that the years ahead would be filled with peace, comfort, and the dignity she had long deserved. She no longer had to wake up each day calculating how to make ends meet, nor did she have to endure the helplessness of watching her son struggle for breath. The sacrifices of her past had been repaid in full, and for the first time in her life, she could truly exhale, knowing that her son had not only built a future for himself but had also secured one for the parents who had given everything to see him succeed.

Adebanjo himself had undergone a transformation that extended beyond his career. The inhaler that had once dictated the rhythm of his life had gradually faded into the past. He still carried one, but it had become more of a precaution than a necessity. The clean air he had worked so hard to advocate for was now his reality. The weight that had once sat on his chest each time he lay down to sleep was gone. His breathing was no longer a constant struggle, no longer an uncertainty. He now knew what it meant to inhale without fear, to move through the world without constantly calculating when he would next need relief.

Adebanjo’s wife had been his anchor throughout his transformation, supporting his relentless pursuit of knowledge and innovation while ensuring that his personal life remained balanced. She understood the depth of his journey, the shadows of his past that had shaped his present. Together, they built a home where their children would never have to experience the fear that had once been his constant companion.

His children would never wake up in the middle of the night gasping for breath, never have to sit out of playtime because running too fast might trigger an attack, never have to ration their physical activities to accommodate their lungs’ limitations. They would grow up in an environment where clean air was a given, not a luxury, where health was preserved not by desperation but by design.

The home he had created for his family was more than just a physical space. It was a manifestation of everything he had fought for–an environment where knowledge and intention had eliminated the struggles that had once seemed inevitable. Every room had been carefully planned, every system optimised to ensure that indoor air quality was maintained at the highest standard. He had designed the very life he had once longed for as a child, not just for himself, but for those he loved.

Thus, Adebanjo’s success was not just measured in his professional accomplishments, but in the life he had been able to create–one where his family no longer had to struggle, where their health and happiness were secured, where his own journey had finally come full circle. **The End!**