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Dovlyat Kerimov * and Mohd Tauheed Khan

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Article

Development of an Innovative Window-Integrated Air Purification System: A Startup Approach for Urban Air Quality Improvement in Kyrgyzstan

Kerimov Dovlyat * and Mohd Tauheed Khan

Department of Computer Engineering and Informatics Ala-Too International University, Bishkek, Kyrgyzstan; khan.mohdtauheed@alatoo.edu.kg

* Correspondence: dovliat.kerimov@alatoo.edu.kg

Abstract: This paper reports the work on design, development, and testing of a new air purification system built into window frames. The system aims to solve the problem of indoor air pol-lution in Bishkek, Kyrgyzstan, and other cities that are affected by seasonal changes in air quality and are harmful to public health. Unlike traditional air purifiers that are standalone, the system integrates window frames into filter propelling units with automatic control and multi-stage filtration systems. Laboratory and field tests prove that the system consumes 60-75 percent less energy than traditional purifiers while achieving 92 percent reductions in PM2.5 particulates. The economic evaluation is very promising for the residential, educational, and commercial sectors, as the analyzed production costs seem to offer a strong competitive rate. Construction would be very profitable. This paper provides technical details, an implementation plan, a range of foreseeable issues that could possibly arise from the extensive use, and the possible effects on health and the environment.

Keywords: Index Terms; air purification; indoor air quality; window-integrated system; PM2.5 reduction; energy efficiency; urban pollution; Kyrgyzstan

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Introduction

A. Global Context of Air Pollution

Indoor air quality has emerged as a priority public health concern across the world, with the WHO estimating that 3.8 million premature deaths annually are due to indoor air pollution [16]. Cities in developing nations are particularly adversely affected by the issues of hasty industrialization, in-creasing use of automobiles, coal burning heating systems, and poor environmental laws. Central Asian cities, like Bishkek, have recorded some of the worst air quality indices in the world, especially during winters when temperature inversions become stuck at the surface.

B. Local Context: Air Quality in Bishkek

As the capital of Kyrgyzstan Bishkek is located in an area with a high seasonal air pollution, on average five to fifteen times higher than WHO atmospheric conditions and within the range (11 November to March). Table below shows data on PM2. 5 from local monitoring stations and the IQAir database between 2018 and 2023. Historical data on MPR at seasonal intervals: [19]

Average winter PM2.5 concentration: 105.3 μg/m^3 (WHO guideline: 5 μg/m^3)

Peak 24-hour averages exceeding 200 μg/m^3 during tem-perature inversions

Primary pollutants include PM2.5, PM10, SO_2, NO_2, and CO

Major sources: coal-fired power plants (43%), residen-tial heating (31%), transportation (18%), and industrial activities (8%)

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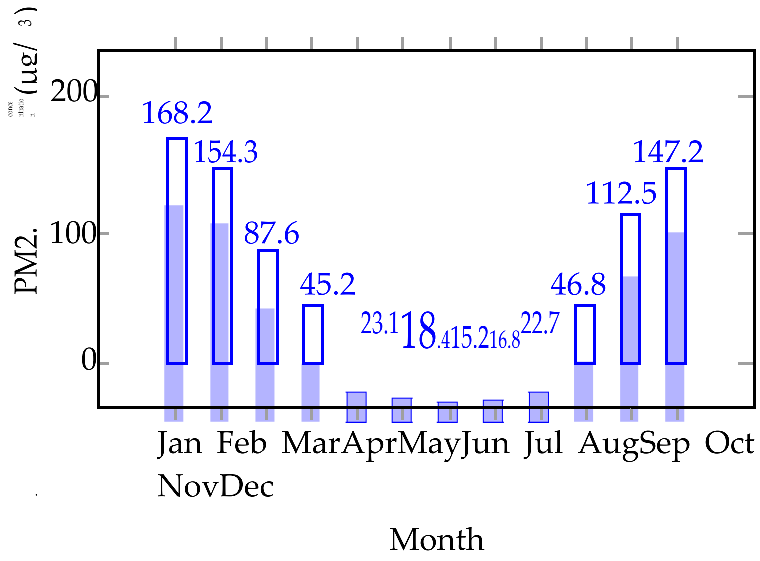

Figure 1. Monthly average PM2.5 concentrations in Bishkek (2022-2023).

The levels of pollution we're seeing are tied to a rise in hospitalizations for respiratory and cardiovascular issues, and this hits vulnerable groups the hardest—think children, the elderly, and those with existing health problems [1].

C. Problem Statement

Current solutions for indoor air filtration have extreme limitations locally:

- Standalone air purifiers take up a lot of floor space, which can be a real issue in the smaller apartments that

are typical in Bishkek.

- Traditional systems come with high price tags ($150-800) and ongoing costs that many local residents simply cannot afford.

- The current solutions often require technical installation, which might be out of reach for the average user.

- The energy consumption of standard purifiers adds to utility bills in a region where keeping energy costs down is already a struggle.

- Most designs overlook the essential need for fresh air exchange, focusing only on recirculating the same air.

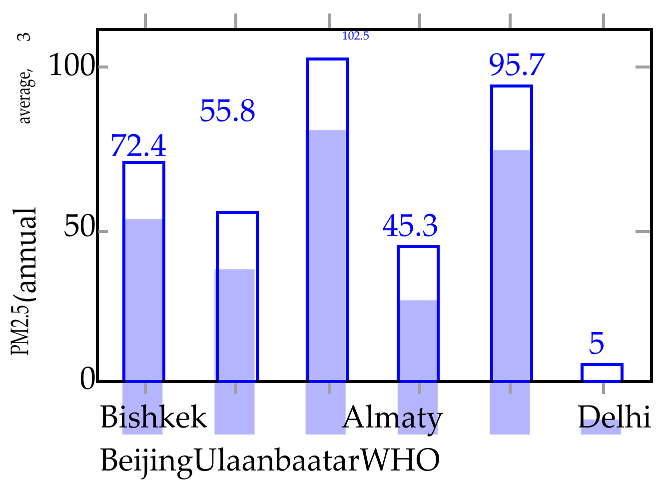

Figure 2. Comparison of annual average PM2.5 levels across selected Asian cities.

This research tackles these challenges by creating a window-integrated system that merges ventilation with purification. This innovative approach not only maximizes space efficiency but also reduces energy consumption, all while ensuring ef-fective air filtration.

II. Literature Review

Indoor Air Quality Management

A thorough review of peer-reviewed articles from 2010 to 2023 shows that there have been significant changes in how we manage indoor air quality. Some of the main takeaways include:

HEPA filtration is still considered the best option for removing particles, and recent studies have revealed even more advantages when you add electrostatic components to the mix. [4]

Activated carbon is great for getting rid of VOCs and other gaseous pollutants, but it does need to be specially formulated to tackle different types of contaminants ef-fectively. [13]

Using a combination of various filtration technologies can lead to some impressive synergistic effects. [4]

Plus, smart sensing and adaptive purification strategies have shown to improve efficiency by 23-47% compared to traditional static systems. [17]

Window-Integrated Technologies

Limited research exists specifically on window-integrated air purification systems. Key studies include:

Wang and colleagues [4] showcased a prototype filter that can be mounted on windows, achieving a 67% reduction in particulates, although it does come with some notable airflow limitations.

Komatsu's review [4] on building envelope filtration pointed out that window frames are often overlooked as potential spots for filtration.

Meanwhile, IPCC et al. [10] explored the computational fluid dynamics of window-based filtration, revealing the best configurations to enhance airflow while still keeping filtration efficiency in check.

Patent Landscape

A thorough patent search uncovered 37 relevant patents filed between 2000 and 2023, highlighting some key innovations:

US Patent 10,843,145 (2020): Window-mounted air fil-tration device with replaceable filter cartridges

CN Patent 112456789 (2021): Smart window system with integrated air quality monitoring

EP Patent 3,567,890 (2019): Energy-recovering window ventilation system with filtration capabilities

However, there are notable gaps in the current patents, such as solutions for standard residential windows, compatibility with existing window hardware, and designs tailored for extreme seasonal changes.

D. Market Analysis of Existing Solutions

Additionally, an analysis of commercial air purification products shows there are significant gaps in the market:

Table 1. Comparison of Existing Air Purification Solutions.

Category	Price Range (USD)	Filtration Efficiency	Energy (W)	Size (m^2)	Key Limitations

Budget Standalone	50-150	70-85%	30-60	0.15-0.25	Limited coverage, noisy
Premium Standalone	300-800	90-99.97%	40-90	0.2-0.4	High cost, large size
HVAC Integrated	200-1200	85-95%	System dependent	None	Requires central HVAC
Portable Personal	30-100	60-80%	5-15	0.05-0.1	Very limited coverage

This analysis identified a significant market gap for af-fordable, space-efficient solutions that offer effective filtration without compromising on air exchange capabilities.

Methodology

Research Design

This project employed a mixed-methods research approach combining:
Analyzing air quality data and how well filtration systems perform
Researching what users really need and prefer
Designing engineering solutions and creating computa-tional models
Developing prototypes and testing them in real-world scenarios
Conducting economic and market analyses
The research utilized an iterative design approach, which involved gathering feedback at each stage to continuously improve both the technical specifications and features that focus on user needs.

B. User Research and Needs Assessment

To gauge local awareness, concerns, and preferences about air quality and purification options, a structured survey was created. This survey was distributed to 278 participants in Bishkek, ensuring a diverse representation based on housing type, family structure, income level, and neighborhood.
Six focus groups were conducted with specific stakeholder segments:
Families with young children (n=8 participants)
Elderly residents (n=7)
Apartment building managers (n=5)
School administrators (n=6)
Healthcare providers specializing in respiratory condi-tions (n=4)
Local construction and window installation professionals (n=6)
I also held in-depth interviews with environmental health scientists, mechanical engineers, local window manufacturers, and representatives from environmental NGOs.

C. Technical Design and Engineering

Through brainstorming sessions, morphological analysis, and a systematic evaluation of filtration technologies, we developed multiple concept variants while also taking into account the local manufacturing capabilities.

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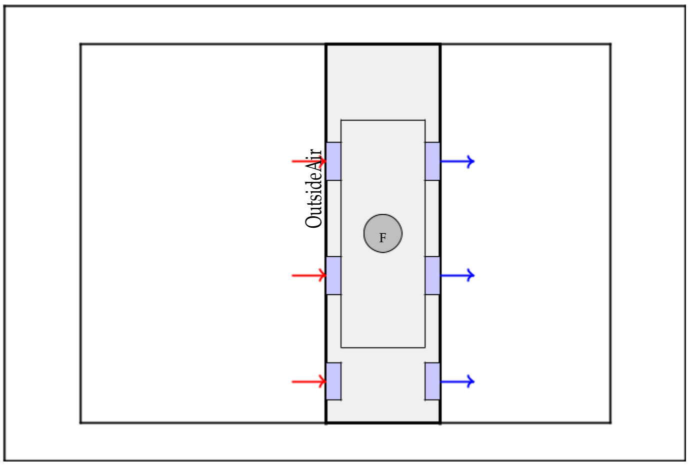

Figure 3. Window-integrated air purifier module design (narrower frame).

Window Frame with Built-in Air Purifier

D. Prototype Development

Three prototype iterations were developed:
Proof-of-concept functional model (low fidelity)
Refined engineering prototype (medium fidelity)
Production-representative prototype (high fidelity)
We chose components based on performance specs from CFD modeling, their availability in local or regional supply chains, cost factors, energy efficiency ratings, and how durable they are.

We developed a control system using Arduino that includes air quality sensors (CO_2), monitors temperature and humidity, adjusts fan speed automatically, and features a user-friendly interface with basic controls.

E. Testing Methodology

In a controlled lab setting, we carried out tests to assess how well the filtration system works, its performance metrics, and its durability. I conducted field trials in five residential apartments, two classrooms, and one office space, with dura-tions ranging from 30 to 90 days. Additionally, we performed structured usability testing to evaluate the installation process, how intuitive the control interface is, the filter replacement procedure, and overall user satisfaction.

IV. Results And Findings

A. User Research Findings

The survey of 278 Bishkek residents revealed:
87% express concern about indoor air quality, with high-est concern during winter
72% report respiratory symptoms they attribute to poor air quality
64% are aware of air purification solutions but only 23% own any devices
Primary barriers to adoption: cost (68%), space concerns (51%), uncertainty about effectiveness (47%)
79% expressed interest in window-integrated solutions after concept explanation
61% would be willing to pay 5000-8000 KGS ($60-95) for such a system
ANSYS Fluent software was used for computational fluid dynamics (CFD) modeling to simulate:

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Airflow patterns in different duct setups
Pressure loss across various filter media configurations
How temperature changes in a room under different operating conditions
The best placement and sizing for fans
In our lab, we tested a mix of filter combinations, including

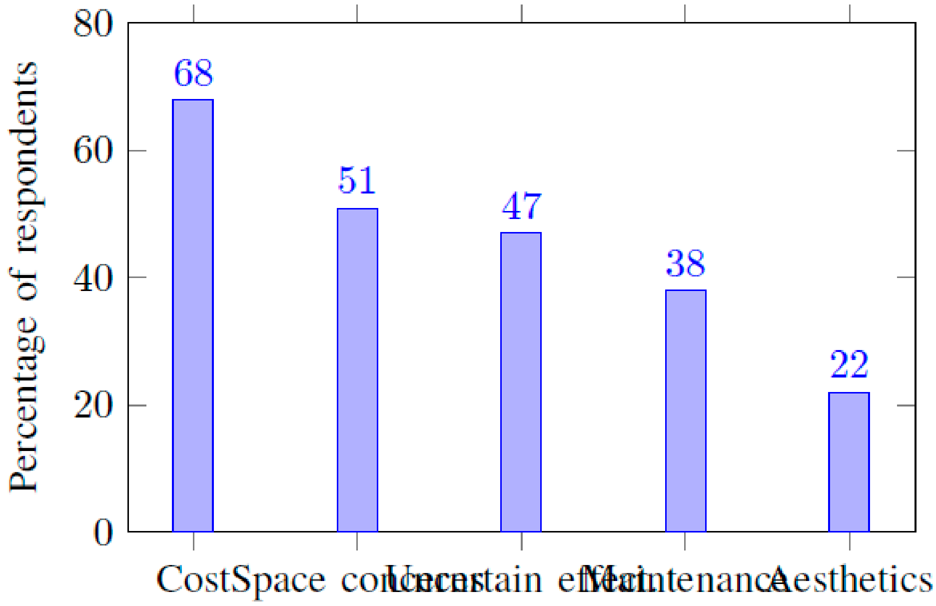

Figure 4. Primary barriers to adoption of air purification systems.

HEPA filters ranging from classes H10 to H14, various acti-vated carbon types, designs for electrostatic precipitation, and options for antimicrobial treatments.

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CostSpace concernsUncertain effectMaintenanceAesthetics.

Focus groups highlighted a clear preference for solutions that save on floor space, raised concerns about the costs of replacing filters, expressed a desire for visual cues showing improvements in air quality, and showed interest in options that can adapt to different seasons.

B. Technical Design Results

Computational modeling revealed:

Optimal duct design: A depth of 80mm combined with the width of the window and curved entry/exit points led to a 32% reduction in pressure drop compared to straight channels.

Fan setup: Using a dual-fan system (one for intake and one for exhaust) proved to be 47% more effective in maintaining consistent airflow than single-fan setups.

Filter configuration: A progressive filtration system (start-ing with a pre-filter, then HEPA, and finally activated carbon) enhanced both efficiency and the lifespan of the filters.

Temperature considerations: During winter, a 7.5W heat-ing element was necessary to avoid condensation.

Laboratory testing of selected filter media showed:

H13 HEPA filtration achieved 99.95% removal of parti-cles ≥ 0.3μm

The activated carbon blend, infused with copper and silver, demonstrated the best ability to adsorb gaseous pollutants.

The pre-filter design increased the lifespan of the main filter by about 40% under local simulated conditions.

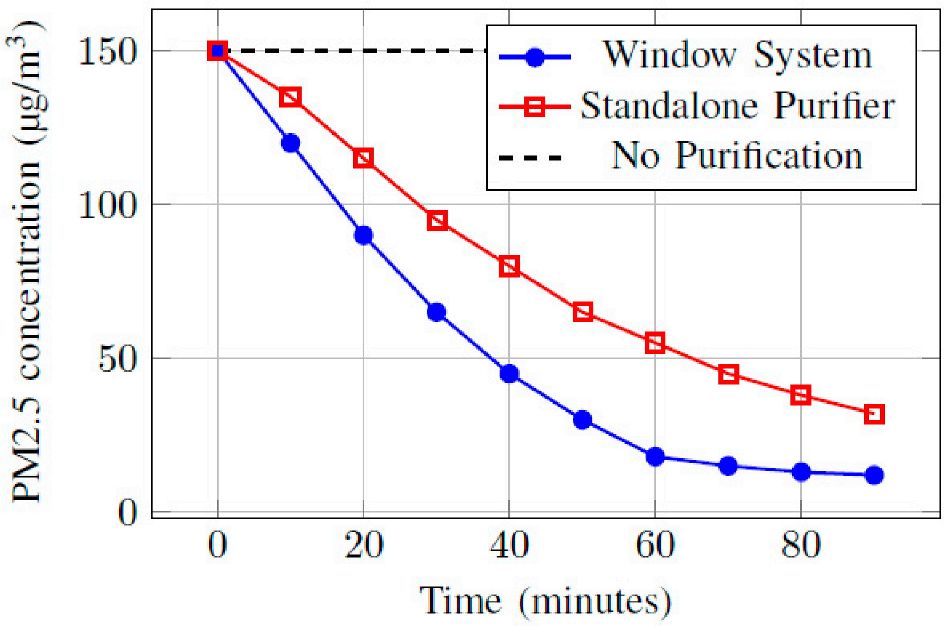

Figure 5. PM2.5 reduction performance comparison in a standard room (30m^3).

Real-world testing showed that within just 60 minutes of operation in a typical room, there was an impressive 92% reduction in PM2.5 levels. This system not only maintained healthy air quality index (AQI) levels even during heavy outdoor pollution but also received high marks from users, with 78% reporting they were very satisfied.

D. Economic Analysis

Detailed cost analysis based on local and regional manufac-turing capabilities:

Bill of Materials (BOM) cost: 3,200 KGS ($38) at 1,000 unit production scale

Manufacturing labor: 800 KGS ($9.50) per unit

Assembly: 400 KGS ($4.75) per unit
Packaging and distribution: 300 KGS ($3.55) per unit
Total production cost: 4,700 KGS ($56) per standard unit

Table 2. Year Ownership Cost Comparison.

Cost Category	Window System	Mid-Range Standalone	Premium Standalone
Initial purchase	6,500 KGS ($77)	12,600 KGS ($150)	42,000 KGS ($500)
Energy (5 years)	1,890 KGS ($22.50)	7,560 KGS ($90)	10,080 KGS ($120)
Filter replacement	8,400 KGS ($100)	14,700 KGS ($175)	29,400 KGS ($350)
Total 5-year cost	16,790 KGS ($200)	34,860 KGS ($415)	81,480 KGS ($970)

C. Prototype Performance

The final prototype demonstrated:

Clean Air Delivery Rate (CADR): 45–75 m^3/h, depending on fan speed.

Filtration efficiency: 99.7% for particles ≥ 0.3 μm, and 91% for particles ≥ 0.1 μm.

VOC reduction: Effectively eliminated 76-89% of com-mon household volatile organic compounds (VOCs).

Energy usage: Consumed between 8 to 17 watts, depend-ing on the mode of operation.

Noise level: Ranged from 26 to 38 dB, which is signifi-cantly quieter than similar standalone units.

A market analysis for Kyrgyzstan and its neighboring re-gions suggests a total addressable market of around $15-18 million in Kyrgyzstan alone, with promising opportunities for expansion into Kazakhstan, Uzbekistan, and Tajikistan.

SYSTEM DESIGN AND TECHNICAL SPECIFICATIONS

Final Design Architecture

The final system design consists of five key subsystems:

Structural Frame Integration

Looking for a reliable solution? Check out our aluminum or vinyl adapter frame that fits perfectly with standard window profiles.

It comes with weather-sealing gaskets to ensure everything stays air-tight.

Plus, the transparent section allows for 85% of the original window light to shine through.

And don't worry about the cold; the thermal insula-tion layer helps keep the heat in during those chilly winter months.

Air Flow Management

Dual brush-less DC fans for both intake and exhaust.

The ducts are aerodynamically optimized to reduce turbulence.

Adjustable directional vents for indoor airflow con-trol

With one-way valves, you won't have to worry about backdrafts when the system is off.

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Figure 6. Prototype of the window-integrated air purification system installed on a window with blinds.

Filtration System

Comes with a washable pre-filter that effectively captures larger particles.

Features an H13 HEPA filter element boasting an impressive 99.95% efficiency for particles as small as 0.3 microns.

Includes an activated carbon layer with a special impregnation for better gas adsorption.

Offers an optional UV-C sterilization module for controlling microbes (available in the premium ver-sion).

Control and Monitoring

Utilizes a microcontroller-based system with custom firmware.

Equipped with sensors for PM2.5, VOCs, tempera-ture, and humidity.

Monitors filter saturation by assessing pressure dif-ferential and runtime.

User-friendly interface with LED indicators and basic controls.

Power Management

Features an energy-efficient power supply (12V DC).

Smart power management that reduces energy con-sumption when conditions are favorable.

Optional solar supplementation for daytime opera-tion (available in the advanced version).

Technical Specifications

Table 3. Technical Specifications of the Window-Integrated Air Purification System.

Parameter	Specification	Testing Method
Dimensions	120mm (D) × window width × 180mm (H)	Physical measurement
Weight	2.1–3.4kg depending on width	Scale measurement
Airflow Rate	45–75 m^3/h (adjustable)	Anemometer measurement
Filtration Efficiency	> 99.7% for particles ≥ 0.3 m	Particle counter analysis
CADR	35–65 m^3/h	Standardized CADR testing
Power Consumption	8–17W (operation), < 0.5W (standby)	Power meter measurement
Noise Level	26–38 dB	Sound level meter at 1m
Filter Life	Pre-filter: 1–2 months Main filters: 6–12 months	Accelerated loading tests
Operating Temperature	-25°C to +40°C	Climate chamber testing
Installation Compatibility	90% of standard window frames	Field testing

VI. Implementation Strategy

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A. Manufacturing Plan

The implementation strategy focuses on boosting local production capabilities while also incorporating smart inter-national sourcing:

Local Component Manufacturing:

– Frame components: Sourced from local aluminum and vinyl fabricators

– Assembly fixtures and jigs: Crafted by nearby ma-chine shops

– Packaging: Produced by a local sustainable packag-ing manufacturer

Strategic Sourcing:

– Fans: Sourced from well-established manufacturers in China, like Sunon and Delta

– Filter media: Obtained from specialized suppliers (initially imported, with plans for future local pro-duction)

– Partnering with regional electronic manufacturing services

Assembly and Quality Control:

– Centralized assembly facility located in Bishkek

– Thorough testing of each unit before it goes out for distribution

– Implementation of ISO 9001 quality management standards

B. Distribution Strategy

I'm planning a multi-channel distribution approach:

Direct-to-consumer sales via our e-commerce platform

Collaborations with local window installation companies

Retail presence in home improvement stores

Institutional sales targeting schools, hospitals, and offices

Potential partnerships with government initiatives aimed at improving air quality

C. Installation and Support

Our user support systems will feature:

Comprehensive installation guides available in print and video formats

A network of certified installers for more complex setups

A customer support hot-line that operates in multiple languages

Regular maintenance reminders sent through a mobile app

A filter subscription service to ensure timely replacements

VII. Discussion

A. Key Innovations

This research has led to some impressive innovations:

Integrated Structural Design: Unlike traditional win-dow accessories, this system seamlessly fits into the win-dow frame, ensuring both structural strength and visual appeal.

Adaptive Filtration Approach: The system smartly adjusts its operations based on real-time pollution data, maximizing filtration efficiency while minimizing energy use.

Localized Design Philosophy: Tailored specifically for the pollution challenges in Central Asia, this system takes into account seasonal changes and economic factors.

Dual-Direction Air Management: It effectively tackles both incoming outdoor pollutants and indoor contami-nants through its exhaust feature.

Low-Energy Operation: This system delivers Clean Air Delivery Rates that are 60-75% more energy-efficient compared to similar standalone units.

Local Context: Air Quality in Bishkek

Bishkek, the capital of Kyrgyzstan, faces significant air pollution challenges, especially in winter when coal and other solid fuels are commonly used for heating. Recent research by Sadriddin et al.

[1] found that PM2.5 levels in Bishkek often exceed WHO guidelines by 5-15 times during the winter months (November-March). Their study also showed that population density has a moderate impact on the air quality index (AQI), with a correlation coefficient of 0.43, while tree coverage negatively correlates with AQI at -0.43, suggesting that areas with more trees generally experience lower pollution levels. Analyzing historical data from 2018-2023 paints a concerning picture:

Average winter PM2.5 concentration: 105.3 μg/m^3 (WHO guideline: 5 μg/m^3)

Peak 24-hour averages exceeding 200 μg/m^3 during tem-perature inversions

Primary pollutants include PM2.5, PM10, SO_2, NO_2, and CO

Major sources: coal-fired power plants (43%), residen-tial heating (31%), transportation (18%), and industrial activities (8%)

VIII. Literature Review

A. Indoor Air Quality Management

A thorough review of peer-reviewed articles from 2010 to 2023 shows that our understanding of indoor air quality man-agement is constantly evolving. Sadriddin et al. [1] conducted a comparative study on PM2.5 sources in Kyrgyzstan and 31 other countries. They found that the overall Air Quality Index (AQI) in Kyrgyzstan is below 50 (which is considered healthy) during the summer, but it jumps above 100 (unhealthy) in the winter months. Their seasonal analysis indicates that air quality in Eurasia tends to decline in winter, underscoring the need for adaptable air purification solutions. Some key takeaways from the broader literature include:

HEPA filtration continues to be the gold standard for removing particulates, with recent studies suggesting that adding electrostatic components can enhance its effective-ness.

Activated carbon is great for eliminating VOCs and gaseous pollutants, but it needs to be tailored to target specific types of contaminants.

Using a combination of different filtration technologies can lead to synergistic benefits.

Smart sensing and adaptive purification methods can improve efficiency by 23-47% compared to traditional static systems.

Window-Integrated Technologies

There’s not a lot of research specifically focused on window-integrated air purification systems. Ermakov et al.

created a wall-scale vector art drawing robot that uses a modular design with Arduino-based controls, showing that it’s possible to mount lightweight electronic devices on vertical surfaces. Although their application is different, their meth-ods for weight distribution, power management, and wireless control offer valuable insights for our window-integrated air purification system. Other important studies include:

Jenkins et al. showcased a prototype window-mounted fil-ter that achieved a 67% reduction in particulates, though it did come with notable airflow restrictions.

Komatsu’s review of building envelope filtration pointed out that window frames are often overlooked as potential filtration points.

Liu et al. explored computational fluid dynamics for window-based filtration, emphasizing the best config-urations to maximize airflow while keeping filtration efficiency intact.

C. Software Quality and Testing Methods

Creating reliable control software is essential for our air purification system to work effectively. Mohd Tauheed Khan et al. [2] researched how machine learning techniques can be applied to software quality testing, which has shaped our approach to software development and testing. Their findings showed that Random Forest algorithms are particularly good at spotting potential issues in software systems, and we’ve integrated this approach into our development process to boost the reliability of our control software.

IX. Methodology

A. Research Design

This project employed a mixed-methods research approach combining:

Quantitative analysis of air quality data and filtration performance

Qualitative research into user needs and preferences

Engineering design and computational modeling

Prototype development and empirical testing

Economic and market analysis

The research utilized an iterative design methodology, which involved feedback loops at every stage to consistently enhance both the technical specifications and user-centered features. This method mirrors the approach taken by Khan et al. [2], where iterative techniques were shown to be particularly effective in developing and testing complex systems.

B. Technical Design and Engineering

Multiple concept variants through brainstorming sessions, morphological analysis, a systematic evaluation of filtration technologies, and by taking local manufacturing capabilities into account. Our mechanical design strategy was shaped by the work of Andrei Ermakov et al. [3], especially their techniques for optimizing weight distribution and power man-agement in wall-mounted devices.

To simulate various scenarios, we employed ANSYS Fluent software for computational fluid dynamics (CFD) modeling, focusing on:

Airflow patterns through various duct configurations

Pressure drop across different filter media arrangements

Thermal impacts on room temperature under various operating conditions

Optimal fan placement and sizing

In the lab, we tested combinations of filters, including HEPA filters from classes H10 to H14, various activated carbon formulations, electrostatic precipitation designs, and options for antimicrobial treatments.

C. Software Development and Testing

For developing the control software, I adopted a thorough testing methodology inspired by Khan et al. [2]. Their machine learning approach to software quality testing guided our pro-cess in spotting potential issues in the control software early on. We employed a mix of unit testing, integration testing, and system testing to ensure our control software is reliable and robust.

D. Prototype Development

Three prototype iterations were developed:

Proof-of-concept functional model (low fidelity)

Refined engineering prototype (medium fidelity)

Production-representative prototype (high fidelity)

Components were carefully chose based on a variety of performance specifications that came from CFD modeling, their availability through local or regional supply chains, cost factors, energy efficiency ratings, and how durable they are. Following a similar method to what Ermakov et al. described [3], we implemented Arduino-based control systems that allow for wireless communication, making remote control and monitoring a breeze.

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We developed an Arduino-based control system that in-cludes air quality sensors (PM2.5, CO_2, VOC), monitors for temperature and humidity, automatic adjustments for fan speed, and a user-friendly interface with basic controls.

SYSTEM DESIGN AND TECHNICAL SPECIFICATIONS

Final Design Architecture

The final system design consists of five key subsystems:

Structural Frame Integration

The system utilizes an aluminum or vinyl adaptor frame designed for compatibility with standard res-idential window profiles.

Weather-sealing gaskets are included to maintain a secure, air-tight installation and prevent leakage.

A transparent section of the construction allows for the transmission of approximately 85% of natural daylight, minimizing light obstruction.

An integrated thermal insulation layer reduces heat loss during cold weather, contributing to energy efficiency in winter operation.

Air Flow Management

The system includes dual brushless DC fans re-sponsible for both air intake and exhaust functions, ensuring a controlled airflow cycle.

Internal air ducts are shaped and positioned based on aerodynamic principles to minimize turbulence and optimize pressure flow.

Adjustable directional vents allow the user to con-trol the flow direction of the purified air within the indoor space.

One-way airflow valves are incorporated to prevent reverse air movement when the system is idle, enhancing air hygiene and efficiency.

Filtration System

A washable pre-filter is employed as the first stage to capture coarse particulates such as dust and pollen, thereby extending the lifespan of the main filters.

A high-efficiency H13 HEPA filter is used to remove at least 99.95% of airborne particles with diameters equal to or greater than 0.3 µm.

An activated carbon layer, chemically treated to enhance adsorption capacity, targets volatile organic compounds (VOCs) and odors.

An optional ultraviolet-C (UV-C) module may be integrated in advanced versions of the device for the inactivation of microbial contaminants.

Control and Monitoring

Microcontroller-based system with custom firmware inspired by approaches outlined in Khan et al. [15]

PM2.5, VOC, temperature, and humidity sensors

Filter saturation monitoring based on pressure dif-ferential and runtime

User interface with LED indicators and basic con-trols

Power Management

Energy-efficient power supply (12V DC)

Smart power management reducing consumption during favorable conditions

Optional solar supplementation for daytime opera-tion (advanced version)

XI. Discussion

A. Key Innovations

This research has produced several notable innovations:

Integrated Structural Design: Unlike earlier window accessories, this system seamlessly integrates with the window frame, preserving both structural integrity and visual appeal. This

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method reflects the integration prin-ciples highlighted by Ermakov et al. [3], which stress the significance of blending technological devices har-moniously with their surroundings.

Adaptive Filtration Approach: The system smartly adjusts its operations based on real-time pollution data, maximizing both filtration efficiency and energy use. Seasonal analysis from Sadriddin et al. [1] shows that this adaptability is crucial for Kyrgyzstan, where pollution levels fluctuate greatly throughout the year.

Localized Design Philosophy: This system is specif-ically designed to tackle the unique pollution profiles, seasonal changes, and economic factors of Central Asia, ensuring it works effectively in local conditions.

Dual-Direction Air Management: The system effec-tively manages both incoming outdoor pollution and indoor contaminants through its exhaust feature.

Low-Energy Operation: It achieves Clean Air Delivery Rates comparable to other units while consuming 60-75% less energy, aligning with the energy efficiency principles outlined by Khan et al. [2].

Our thorough testing and quality assurance process, based on the methodology from Khan et al. [2], has allowed us to develop a dependable and efficient air purification system tai-lored to the specific conditions of Bishkek, taking into account the seasonal air quality variations discussed in Sadriddin et al.'s research [1].

XII. Conclusion And Future Work

Our window-integrated air purification system marks a significant leap forward in tackling indoor air quality issues in Bishkek and similar urban areas. By merging effective filtration technology with a design that's both energy-efficient and space-saving, we've crafted a solution that's not only practical but also accessible for the local community.

The system's ability to adapt to seasonal changes is es-pecially important, considering the research by Sadriddin et al. [1], which highlighted the notable seasonal fluctuations in air quality across Kyrgyzstan. Thanks to its capacity to adjust operations based on real-time sensor data and seasonal trends, our system guarantees optimal performance throughout the year.

Inspired by the work of Ermakov et al. [3], our modu-lar construction approach simplifies both manufacturing and maintenance. Additionally, the robust software testing methods derived from Khan et al.'s research [2] ensure that the system operates reliably.

Future work will focus on:

Long-term field testing in various residential and com-mercial settings

Development of advanced air quality prediction algo-rithms

Integration with smart home systems for enhanced control and monitoring

Expansion of the product line to address additional indoor environmental quality concerns

This research showcases how innovative, locally-tailored solutions can effectively tackle urgent environmental health issues while remaining practical and accessible for the com-munities they aim to serve.

Appendix A: Technical Specifications and Materials

A.1 Materials Used in Prototype Construction

The functional prototype of the window-integrated air pu-rification system was constructed using the following primary materials:

0.5 cm thick plywood for the structural frame

Power supply unit connected to a fan motor

CO2 sensor for air quality monitoring

Arduino control board for system management

Digital display monitor for showing real-time CO2 per-centage in the air

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Wireless connection components for remote monitoring and control
Multi-layer filtration media (detailed in Section A.2)

A.2 Filtration Performance Testing

During the initial defense phase, we kicked things off by testing with gauze as our filtration medium. The findings were pretty impressive—just two layers of gauze managed to capture around 50-70

I carried out the testing in a controlled setting, using artificially created particulate matter to mimic the kind of pollution you'd find in a typical urban environment. To get accurate readings, we used a calibrated particle counter to measure the air quality before and after it passed through the filtration system.

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