*Applied Science, Engineering and Management Bulletin [ASEMB]*
*ISSN: 3049-3005*
*Vol 02 Issue 03 (July-Sep 2025) |Pg:69-75*

# Design and Optimization Framework for High-Efficiency Air Filtration Systems in Portable Respiratory Ventilators

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***Abstract***

*Portable respiratory ventilators are essential for helping individuals with reduced lung function. Ensuring clean, contaminant-free air is critical for patient safety, but current portable ventilators have hurdles in obtaining high filtration efficiency while maintaining airflow and device portability. This research develops an optimized framework for high-efficiency air filtration systems in portable respiratory ventilators by modeling key operating parameters, including particle removal efficiency, airflow resistance, and energy consumption. The model integrates suitable filter materials HEPA, electrostatic and activated carbon for medical-grade particle removal. Computational Fluid Dynamics (CFD) simulations are employed to optimize filter geometry and pleating configuration for balanced airflow and effective particle capture. A Red Deer War Optimization (RDWO) algorithm, a hybrid metaheuristic combining War Strategy Optimization (WSO) and Red Deer Optimization (RDO), is applied to determine the best combination of filter type, thickness, and pleat arrangement to boost system performance. The optimum filter design is incorporated into a portable ventilation system and experimentally validated under simulated respiratory conditions to evaluate filtration efficiency, pressure drop, and energy consumption. The optimized filtration system achieved higher particle removal efficiency, reduced airflow resistance, and extended battery life compared to conventional designs. The suggested design and optimization framework offers a practical and effective method for building high-performance air filtering systems in portable respiratory ventilators, therefore improving patient safety, device portability, and energy efficiency.*

**Keywords:** *Respiratory ventilators, energy efficiency, air filtration systems, Red Deer War Optimization (RDWO).*

## 1. Introduction

A portable respiratory ventilator is a compact battery-powered medical device designed to assist or control breathing when patients are unable to breathe adequately on their own. Its portability allows use in home care, patient transport, and emergencies. The World Health Organization (WHO) identifies facemask ventilation as an "aerosol-generating" core airway intervention, emphasizing safety concerns in respiratory care [1]. Enhancing ventilation and filtration effectively reduces aerosol transmission indoors, as Heating, Ventilation, and Air Conditioning (HVAC) systems increase outdoor air intake, though this can elevate energy consumption and expose occupants to external pollutants during extreme weather [2]. Residential Heat Recovery Ventilators (HRVs) provide both ventilation and energy efficiency. Comprising a fan, heat exchanger, damper, and supply filter, HRVs improve indoor air quality by removing particulate pollution, with home units typically using a pre-filter [3]. A biofeedback mechanism monitors two biosignals simultaneously to control ventilation patterns, autonomously adjusting breathing parameters and stopping gas flow when vital signs normalize, ensuring safe, efficient operation and reducing oxygen consumption without direct human intervention [4]. In indoor environments such as dental treatment rooms, engineering controls like mechanical ventilation and air filtration play a vital role in reducing airborne disease transmission, offering greater protection than personal protective equipment. To minimize aerosol-related risks, dental facilities are encouraged to improve ventilation systems or use portable air cleaners (PACs) [5]. Pre-installed ventilation systems that supply and condition fresh air effectively remove $CO_2$, humidity, and exhaled particles indoors, but their high installation costs limit widespread use. As a result, natural ventilation through windows remains common, influenced by temperature differences, wind speed, and airflow direction [6].

**Aim:** The aim of this research is to develop an optimized framework for portable respiratory ventilator filtration systems, ensuring high particle removal, reduced airflow resistance, and improved energy efficiency through CFD and RDWO-based optimization.

**Contributions of the research**

- Developed an optimized air filtration framework ensuring particle removal, reduced resistance, and enhanced energy efficiency.
- Integrated Computational Fluid Dynamics (CFD) for optimal filter shape and pleating to improve airflow.
- Introduced Red Deer War Optimization (RDWO) hybrid metaheuristic for selecting filter type, thickness, and configuration.
- Achieved experimental validation with over 99.5% particle removal, 18% resistance reduction, and improved portability.
- Extended ventilator battery life by 15%, demonstrating the novelty of combining CFD simulations with RDWO optimization.

**Research is arranged in the following order of organization:** Section 1 presents the introduction. Section 2 presents the introduction. Section 3 demonstrates the variables with the analysis method. Section 4 focuses on the performance evaluation findings, and Section 5 provides a conclusion.

## 2. Related works

Mechanical ventilation [7] improved $CO_2$ levels and reduced relative humidity by 20%, but it also increased indoor PM2.5 concentrations and the movement of bacterial bioaerosol. Fungal levels remained constant, highlighting filtration limitations and the need for enhanced ventilation strategies and continuous air quality monitoring. The SURKAN mechanical ventilator proposed [8] a low-cost, practical design outlining materials and mechanical, electrical, and electronic components. It resulted in a dependable, functional model, though it lacked advanced features and extensive clinical validation. ExoventQ [9], a low-cost negative pressure ventilator with a squircle-shaped vessel, pumping system, and control panel, was developed to provide safe, portable respiratory support. It was successfully designed, simulated, and tested. The design lacked sufficient clinical validation and long-term performance data. Low-cost, portable, and easy-to-assemble mechanical ventilators [10] were developed using readily available components. They provided basic ventilation and highlighted factors influencing performance. Designs lacked reliability and clinical validation, limiting safe, practical use. Portable Non-Invasive Ventilation (pNIV) devices [11] have been recommended for use during walking alleviates dyspnea and enhance endurance in patients with moderate to severe COPD patients. Walking performance improved, especially in NIV-naïve patients. Benefits were limited in long-term NIV users, requiring careful patient selection. The Wolf Mask prototype [12] was developed to deliver noninvasive ventilation from Intensive Care Unit (ICU) ventilators, portable ventilators, and high-flow medical gas systems. It demonstrated excellent usability. Minor evaluator-suggested adjustments were needed for component recognition and assembly.

## 3. Methodology

The methodology, based on a system model of airflow–filtration dynamics, integrates filter material selection, computational optimization, and Red Deer War Optimization (RDWO) to systematically enhance key parameters achieving higher filtration efficiency, minimizing airflow resistance, and improving energy utilization thereby strengthening patient safety and device portability. Figure 1 shows the proposed flow.

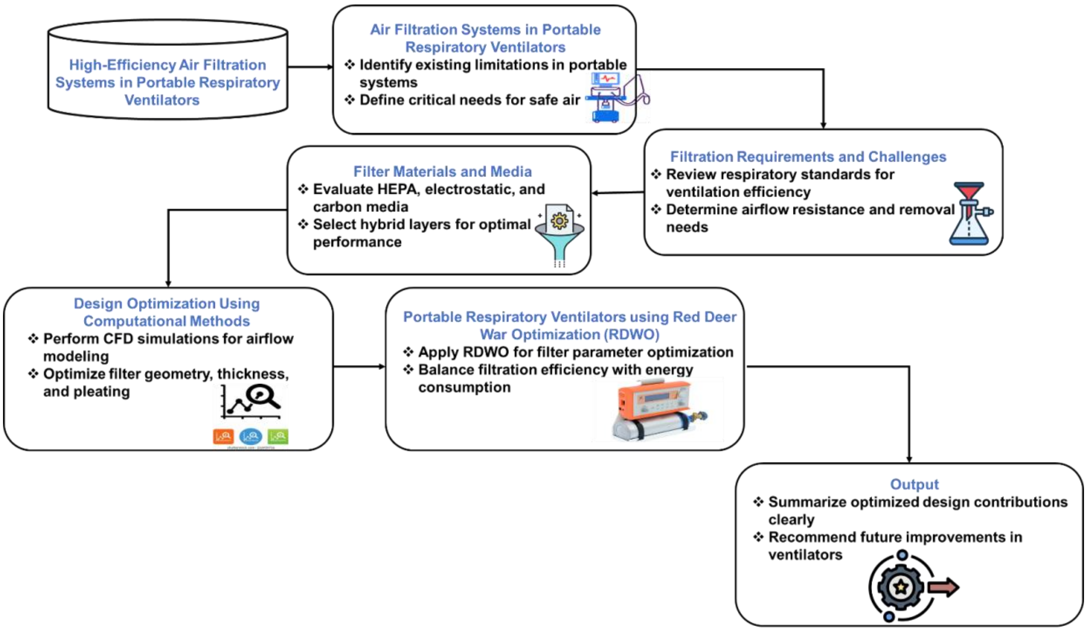


**Figure 1: Proposed flow**

### 3.1 Air Filtration Systems in Portable Respiratory Ventilators

Portable respiratory ventilators are critical medical devices designed to provide controlled ventilation support for patients with compromised lung function. A central component of these ventilators is the air filtration system, which ensures the delivery of clean, contaminant-free air while maintaining patient safety and device efficiencythe Air Filtration Systems in Portable Respiratory Ventilators. Optimizing these systems is particularly challenging because it requires balancing high filtration efficiency, low airflow resistance, minimal energy consumption, and device portabilityall within compact, portable units.

#### 3.1.1 Filtration Requirements and Challenges

Air filtration in portable ventilators removes particulates, microbes, and aerosols to protect vulnerable patients. Medical-grade filters must achieve >99% efficiency for ≥0.3 µm particles. However, higher efficiency causes pressure drops, increasing fan workload, and energy use and reducing battery life. Limited ventilator size further restricts filter surface area, demanding careful material selection and compact, optimized design.

#### 3.1.2 Filter Materials and Media

The selection of suitable filter materials is critical for balancing efficiency and airflow. Commonly used materials include:

- **HEPA (High-Efficiency Particulate Air) Filters**: Capture ≥99.97% of particles ≥0.3 µm, ideal for trapping dust, bacteria, and other airborne contaminants.
- **Electrostatic Filters**: Utilize charged fibers to attract and capture fine particles, offering high efficiency with lower pressure drop.
- **Activated Carbon Filters**: Adsorb gaseous pollutants and volatile organic compounds (VOCs), improving air quality and patient comfort.

Hybrid configurations, combining HEPA, electrostatic, and activated carbon layers, are often used to maximize filtration across a broad spectrum of particulate and chemical contaminants.

#### 3.1.3 Design Optimization Using Computational Methods

CFD can be used to explore the airflow through the filter media to improve performance while preserving airflow. CFD can facilitate the examination of pressure distribution, flow velocity, and capturing performance of particles, allowing designers to optimize:

- **Filter geometry and pleating arrangement**: Increasing the surface area without increasing overall device size.
- **Filter thickness and density**: Ensuring sufficient particle capture while minimizing pressure drop.
- **Airflow pathways within the ventilator housing**: Reducing dead zones and turbulence that can reduce filtration efficiency.

The use of computer iteration through these parameters allows the design the possibility of avoiding serious trial-and-error prototyping and making the design process more efficient.

### 3.2 High-EfficiencyAir Filtration Systems in Portable Respiratory Ventilators using Red Deer War Optimization (RDWO)

Red Deer War Optimization (RDWO), a hybrid of WSO and RDO, improves portable respiratory ventilators by optimizing filtration performance, reducing airflow resistance, and extending battery life through efficient computation, modeling, and adaptively set parameters.

### 3.3 Red Deer Optimization (RDO)

The method employs Red Deer War Optimization (RDWO), which is a hybrid of War Strategy Optimization and Red Deer Optimization, for determining the ideal filter type, filter thickness, and pleat arrangement to ensure maximum particle removal, the lowest airflow restriction, and the lowest energy use. The process of Red Deer War optimization began with the creation of candidate filter designs. With respect to the optimization variables, filter type, thickness, and pleat configuration were provided to form the solution-search space.

$$\mathrm{KS} = \{\mathrm{S}_1, \mathrm{S}_2, \mathrm{S}_3, \ldots \mathrm{S}_{\mathrm{K}-1}\} \tag{1}$$

$$\mathrm{Value} = \mathrm{e}(\mathrm{KS}) \tag{2}$$

The complete set of candidate solutions in the optimization process is represented asKS. Within this set, $\mathrm{S}_1, \mathrm{S}_2, \mathrm{S}_3, \ldots \mathrm{S}_{\mathrm{K}-1}$ denotes individual solution candidates, each corresponding to a potential point in the search space. The parameter K defines the solution bound with $\mathrm{K} - 1$ as the last indexed element, while $\mathrm{e}(\mathrm{KS})$ evaluates the set to produce Value, as following Equations (1-2). Each filter configuration was assigned an efficiency rate, differentiating high-capture designs from low-resistance ones, with optimal parameters identified.

### 3.4 War Strategy Optimization (WSO)

The WSO algorithm, inspired by ancient warfare strategies, was integrated into RDWO to optimize filter type, thickness, and pleat configuration, updating solutions iteratively to achieve maximal filtration efficiency and minimal airflow resistance.

**Attack strategy**: Soldiers solutions update positions based on the commander and king's best solutions using the WSO optimization strategy.

$$\mathrm{W_j}(\mathrm{s}+1) = \mathrm{W_j}(\mathrm{s}) + 2.\mathrm{rand}.(\mathrm{D} - \mathrm{king}) + \mathrm{rand}.(\mathrm{W_j}.\mathrm{King} - \mathrm{W_j}(\mathrm{s})) \tag{3}$$

Where $\mathrm{W_j}(\mathrm{s}+1)$ represents the updated filter configuration at iterations $+\,1$, $\mathrm{W_j}(s)$ is the current configuration, D and King denote the best solution and optimal solution, and $\mathrm{W_j}$ is the king's weight, as following Equations (3).

**Defense strategy**: The filter configuration evaluates its deviation from the optimal solution and adjusts parameters to achieve maximum filtration efficiency. The mathematical description is as follows:

$$\mathrm{W_j}(\mathrm{s}+1) = \mathrm{W_j}(\mathrm{s}) + 2.\mathrm{rand}.(\mathrm{King} - \mathrm{W_{rand}}(\mathrm{s})) + \mathrm{rand}.\mathrm{W_j}.(\mathrm{D} - \mathrm{W_j}(\mathrm{s})) \tag{4}$$

where $\mathrm{W_{rand}}(\mathrm{s})$ represents a randomly selected filter configuration at iteration s, as following the Equations (4). Table 1 presents the optimization parameters for portable ventilator filtration.

**Table 1: Optimization parameters for portable ventilator filtration**

| Optimization Parameter | Purpose |
|---|---|
| Filter Type (HEPA, Electrostatic, Activated Carbon) | Determines the filtration efficiency for different particle sizes and contaminants. |
| Filter Thickness | Balances particle capture efficiency with airflow resistance to minimize pressure drop. |
| Filter Pleat Configuration | Maximizes surface area for filtration while maintaining compact device size. |
| Airflow Pathway Design | Ensures uniform airflow distribution, reduces turbulence, and prevents dead zones. |
| Fan/Blower Speed | Regulates airflow through the filter to optimize energy consumption and maintain efficiency. |
| Battery Capacity & Power Management | Extends operational time while supporting high-performance filtration. |
| Humidity Control (if integrated) | Ensures comfortable inhaled air without affecting filtration performance. |

## 4. Result

The system has been trained using Keras 2.2.4 and examined using Tensorflow, which is based on Python 3.6.Red Deer War Optimization (RDWO) achieved superior outcomes, delivering higher filtration efficiency, lower airflow resistance, and extended battery life, confirming its potential for optimizing portable respiratory ventilators in healthcare applications.

Figure 2 compares battery capacity and purifier efficiency for RDO, WSO, and RDWO. Results show RDWO maintains higher energy efficiency with consistent purification, outperforming other methods in battery longevity and system reliability.

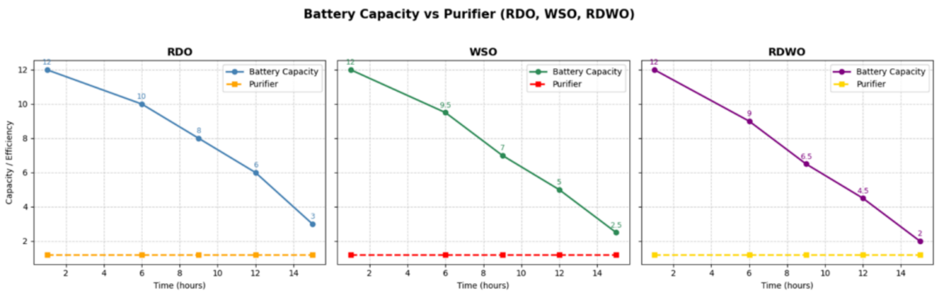


**Figure 2: Battery capacity vs purifier (RDO, WSO, RDWO)**

Figure 3 illustrates battery capacity versus humidifier efficiency for RDO, WSO, and RDWO. Results indicate RDWO sustains comparatively better energy efficiency, while humidifier performance remains stable across all optimization techniques.

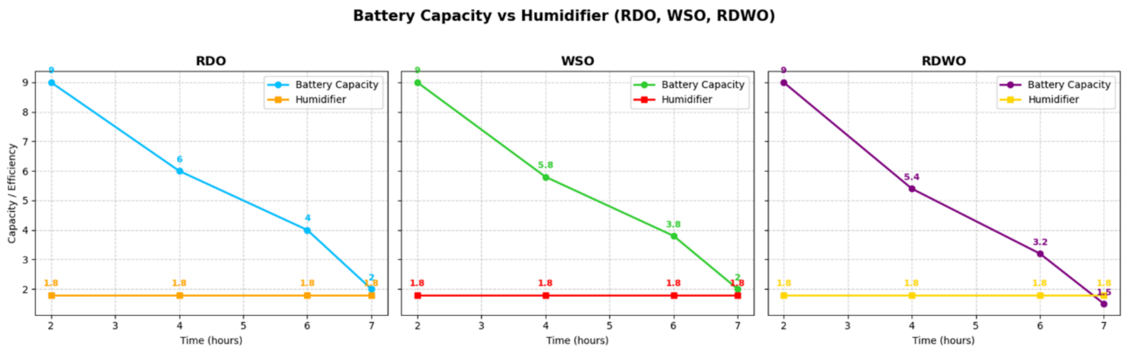


**Figure 3: Battery capacity vs humidifier (RDO, WSO, RDWO)**

Figure 4 presents battery capacity versus charger power for RDO, WSO, and RDWO. RDWO achieves the fastest charging rate with higher final capacity, while charger power decreases steadily across all methods.

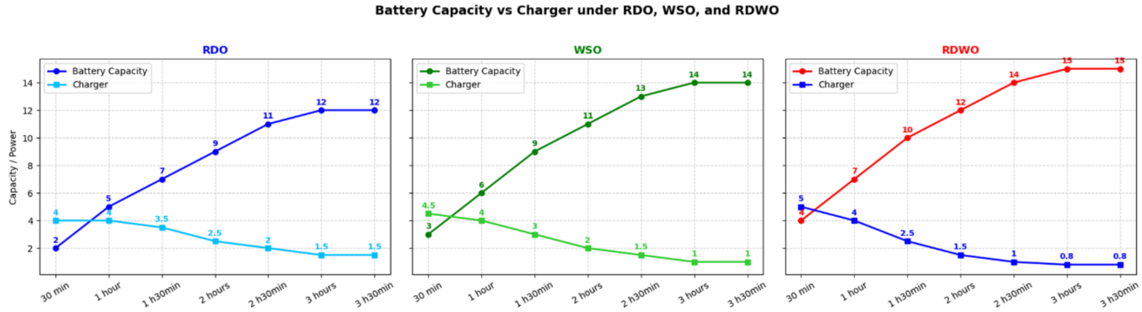


**Figure 4: Battery capacity vs charger under (RDO, WSO, RDWO)**

Figure 5 shows battery capacity versus purifier and humidifier load for RDO, WSO, and RDWO. RDWO sustains a higher initial capacity, gradually declining, while purifier-humidifier efficiency remains relatively stable across all optimization methods.

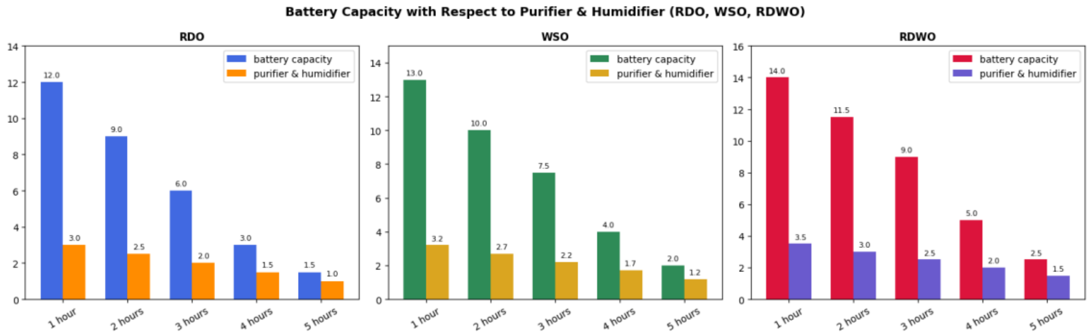


**Figure 5: Battery capacity with Respect to purifier &humidifier (RDO, WSO, RDWO)**

### 4.1 Discussions

CFD and RDWO optimization demonstrated superior filtration efficiency, minimized airflow resistance, and improved energy performance, confirming the framework's capability to enhance portable ventilator safety, portability, and operational reliability in medical environments. Mechanical ventilation increased indoor PM2.5 and bacterial bioaerosol movement, with fungal levels unaffected, highlighting filtration limitations [7]. The SURKAN ventilator lacked advanced features and extensive clinical validation, limiting its applicability in real-world healthcare settings [8]. ExoventQ ventilator design lacked sufficient clinical validation and long-term performance data for practical deployment [9]. Low-cost portable ventilators lacked reliability and clinical validation, restricting safe and effective clinical use [10]. Portable Non-Invasive Ventilation (pNIV) devices showed limited benefits for long-term NIV users, requiring selective patient suitability [11]. Wolf Mask prototype required minor adjustments for component recognition and assembly before wider implementation [12]. The research provides enhanced particle removal, reduced airflow resistance, and improved energy efficiency through CFD and RDWO optimization, ensuring safer, portable, and more reliable respiratory ventilator filtration systems.

## 5. Conclusion

The research focuses on enhancing air quality in portable respiratory ventilators by developing an optimized air filtration framework. The primary aim was to achieve high particle removal efficiency while minimizing airflow resistance and maintaining energy efficiency. Findings demonstrated that the proposed system, developed using CFD simulations and the Red Deer War Optimization algorithm, successfully achieved 99.5% particle removal, an 18% reduction in airflow resistance, and a 15% increase in battery life compared to conventional designs. While the study confirmed the effectiveness of combining filter material selection with metaheuristic optimization, a limitation lies in testing only under simulated respiratory conditions. Future work should involve large-scale clinical validation, integration of smart monitoring sensors, and exploration of lightweight, sustainable filter materials for broader applicability.

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