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Research Article

Effectiveness of Air Filters in Allergic Rhinitis: A Systematic Review and Meta-Analysis

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Previous studies have evaluated the effectiveness of air filters in mitigating the symptoms of allergic rhinitis (AR). However, these studies have yielded inconsistent results. This systematic review and meta-analysis was conducted to assess the effectiveness of air filters for patients with AR. For this, we comprehensively searched the PubMed, Embase, and Cochrane Library databases to identify relevant articles. The results are presented in terms of standardized mean difference (SMD) and 95% confidence intervals (CI) values with the fixed-effects model (FEM) and random-effects model (REM). Eight randomized controlled trials were included in our meta-analysis. Of these, three had a parallel design and five had a crossover design. Regarding clinical outcomes, pooled analyses performed using patients' nighttime and daytime symptom scores revealed SMD values of −0.21 (95% CI: −0.35 to −0.07 (FEM) and −0.35 to −0.08 (REM)) and −0.16 (95% CI: −0.30 to −0.03 (both FEM and REM)), respectively. However, no significant changes were noted in the SMD values when assessing medication use, quality of life (QoL), or peak expiratory flow rate (PEFR). In conclusion, air filters may help alleviate symptoms associated with AR; however, their effects on medication use, QoL, and PEFR appear to be limited. This systemic review and meta-analysis is registered with CRD42022380560.

1. Introduction

Allergic rhinitis (AR) is an inflammatory condition affecting the nasal mucosa. This condition can be induced by exposure to various allergens, such as pollen, dust mites, dust particles, and animal dander [1]. AR can manifest as an intermittent or a persistent condition depending on its duration, as a mild or moderate to severe condition depending on its severity, and as a seasonal or perennial condition depending on the timing of allergen exposure [2, 3]. The global prevalence of AR ranges from 3.6% to 54.5% [4] and varies depending on age, sex, geographic location, and household income [5–7]. Typical symptoms of AR include nasal congestion, repeated sneezing, rhinorrhea, and nasal itching [3]. Additionally, individuals with AR may experience postnasal drip, watery eyes, facial discomfort or pressure, and ear

discomfort or pressure [5]. These symptoms can lead to sleep disturbances, fatigue, and cognitive or psychiatric problems that affect patients' quality of life (QoL) [8–10]. Consequently, the World Health Organization recommends allergen avoidance as a strategy for managing AR [11].

Air filters can be operated mechanically or electronically for the removal of particles dispersed in the air and are thus used for allergen avoidance [3, 12]. These devices are widely applied in air conditioners or heaters or are used as independent equipment in both residential and public spaces. Experts from the American College of Allergy Asthma and Immunology have stated that air filters can reduce the levels of indoor ambient particles, thus potentially mitigating the progression of allergic airway disease [13]. Moreover, air filtration may offer relief from symptoms associated with AR. In the systematic reviews concerning preventive measures for perennial AR caused by indoor dust mites, two trials involving air filtration devices were included [14, 15]. In one trial, nine house dust mites- (HDMs-) sensitized AR patients were randomly assigned to either the experimental group, which used air filtration devices with HEPA filters in addition to home cleaning, or the control group, which performed only regular home cleaning. The results revealed a significant reduction in HDMs allergen levels in the environment, along with notable improvements in nasal symptom scores within the experimental group [16]. In the other trial, 40 HDMs-sensitized AR patients were randomized into the experimental group using air filtration devices with HEPA filters, while the control group had nonfunctional air filtration devices. Although the results showed a nearly 70% reduction in suspended particles greater than 0.3 micrometers in the environment for the experimental group, there was no significant reduction in symptoms related to sneezing, runny nose, nasal congestion, itchy eyes, ears, nose, throat, asthma, or medication usage when compared to the control group [17]. Symptoms related to perennial AR, including nasal symptoms, exhibited varying improvement across these trials included in the systematic reviews. Previous non-randomized controlled studies on the effectiveness of air filtration devices for AR patients also revealed inconsistent results on symptoms associated with AR. Morris et al. performed a study on 14 AR patients sensitized to ragweed. They placed air filtration devices equipped with HEPA filters in the sleeping area and conducted a 3-week study. The results revealed a significant improvement in AR-associated symptom scores, QoL, and daytime sleepiness [18]. Rao et al. conducted a study involving 46 patients with allergic respiratory diseases. They provided these patients with air purifiers equipped with photoelectrochemical oxidation and observed statistically significant improvements in both nasal and eye symptoms [19]. Luo et al. studied 32 AR patients allergic to HDMs who used air purifiers with HEPA filters for 4 months. The results showed reduced HDMs levels in rooms and bedding, lower indoor particle concentrations, and improved activity and problem-solving abilities. However, improvements in eye symptoms, mood, and sleep were not statistically significant [20].

Regarding the studies on the effectiveness of air filters for AR patients, certain outcomes have revealed different results, and these outcomes have not been quantitatively analyzed in prior systematic reviews. Therefore, we conducted this systematic review and meta-analysis to evaluate the effectiveness of air filters in patients with AR.

2. Methods

2.1. Search Strategy and Study Eligibility. This systematic review and meta-analysis study was registered on PROSPERO (CRD42022380560) and was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines (Table S1) [21]. The literature was searched without any language restrictions. The PubMed, Embase, and Cochrane Library databases were comprehensively searched (from inception up to November 1, 2022) to identify relevant articles. For this, we searched the Medical Subject Headings terms "allergic rhinitis" and "air filter" along with relevant text words. Detailed information on the search strategy is presented in Tables S2–S4. Additionally, we manually reviewed the references of retrieved articles to identify any additional articles meeting our inclusion criteria.

2.2. Inclusion and Exclusion Criteria. We included randomized control trials (RCTs) that met the following criteria: (1) including patients with AR; (2) using air filters for interventions; (3) reporting outcomes of interest, which could be extracted directly from the text or indirectly calculated from published data; and (4) applying an RCT design.

We excluded articles that were duplicated in the databases, those with titles or abstracts unrelated to our research, and those whose full texts could not be accessed.

2.3. Data Extraction and Outcomes. Two authors (M.Y.S. and H.W.H.) independently extracted patients' basic data from the included studies. Any disagreements were resolved through discussion with a third author (W.C.L.). Data that could not be extracted directly from the text but could be inferred from the figures were retrieved using WebPlotDigitizer version 4.5 (https://automeris.io/WebPlotDigitizer/) [22]. The basic data included information on the first author's name, publication year, country, study design, AR type, sample size, gender distribution, patients' age, intervention and control groups, operating time, and study period.

Data on primary (e.g., symptom scores) and secondary (e.g., medication use, rhinoconjunctivitis-specific QoL, and peak expiratory flow rate (PEFR)) outcomes were obtained from the included studies.

2.4. Quality Assessment and Risk of Bias. Two authors (M.Y.S. and S.Y.C.) evaluated the risk of bias (RoB) of the included studies by using the Cochrane RoB 2.0 tool [23]. For parallel RCTs, five bias domains were evaluated: randomization process, deviations from intended interventions, missing outcome data, outcome measures, and reported result selection. For crossover RCTs, in addition to the aforementioned five domains of bias, bias arising from period and carryover effects were evaluated. Each domain was coded as having a low, some concerns, or high RoB.

Any disagreements were resolved through discussion with the senior author (C.C.).

2.5. Data Synthesis and Statistical Analysis. For RCTs with a parallel design, data were extracted from both experimental and control groups. For RCTs with a crossover design, data were collected separately for the experimental and control periods. Data regarding standard deviations (SDs) were missing in one of the included studies [24], and we could not obtain these data even after contacting the authors of that study. Therefore, considering that studies have reported a linear relationship between the mean and SD values [25, 26], we performed linear regression to estimate the missing data. Subsequently, a study that provided complete patient data [17] was included as a reference to compute a correlation coefficient in accordance with the Cochrane Handbook [27]. Then, we applied this coefficient to the other studies to calculate the standard error. Statistical analyses were performed using RStudio (version 4.2.1; R Foundation for Statistical Computing, Vienna, Austria) [28] and the *metcont* function of the *meta* package [29]. The identified studies were synthesized using a fixed-effects model (FEM) and random-effects model (REM). The results are presented in terms of the standardized mean difference (SMD) and 95% confidence interval (CI) values.

We used Cochran's Q test and I^2 statistics to evaluate the levels of heterogeneity among the included studies. The level of significance for Cochran's Q test was set at $p < 0.1$. The I^2 values were divided into the following ranges for heterogeneity evaluation: 0%–40%, might not be important heterogeneity; 30%–60%, moderate heterogeneity; 50%–90%, substantial heterogeneity; and 75%–100%, considerable heterogeneity [27].

We performed sensitivity analyses to investigate whether the pooled effect sizes would change if the estimates for the missing SD data were removed, and the correlation coefficient was adjusted among the crossover studies. In addition, we performed subgroup analyses by combining relevant estimates for similar patient subgroups across trials. Furthermore, meta-regression analyses were conducted by treating some variables as covariates to identify factors associated with heterogeneity. Finally, any potential publication bias was assessed using Egger's test for funnel plot asymmetry [30].

3. Results

3.1. Study Selection. Figure 1 presents an overview of the literature search process. We identified 324 studies through our initial search. After the removal of duplicates, 220 studies remained. Of these, 193 were excluded because their titles and abstracts were unrelated to the scope of the present systematic review and meta-analysis. Furthermore, the full text of one of the remaining 27 articles was not accessible. Therefore, we assessed the full texts of the 26 remaining studies for eligibility. We excluded studies that did not meet the participant-related criteria ($n = 3$), the intervention-related criteria ($n = 12$), and the study design-related criteria ($n = 3$). Detailed information regarding these exclusions is presented in Table S5. Finally, eight RCTs [16, 17, 24, 31–35] were included in our analysis.

3.2. Study Characteristics. Table 1 presents the characteristics of the eight RCTs that were included in our study. These trials were published between 1978 and 2020. Of these RCTs, two were conducted in Asia, two in Europe, and four in the United States. Three RCTs had a parallel design [32–34], and five had a crossover design [16, 17, 24, 31, 35]. The sample sizes ranged from 9 to 90. The mean age of the included patients was 16–39.1 years. Patients' allergen sensitivity profiles varied slightly across the RCTs. In five RCTs, patients were sensitive to indoor allergens such as HDMs and pets (e.g., dogs and cats) [16, 17, 32, 34, 35]. By contrast, in the remaining three RCTs, patients were sensitive to outdoor allergens (e.g., pollen) [24, 31, 33]. The included patients were divided into intervention and control groups. The intervention groups received air purifiers, air cleaners, air ventilators, and pillows equipped with air filters, whereas the control groups were subjected to no air filter interventions. In each RCT, the devices were used for more than 8 hours per day. The study periods ranged from 4 to 16 weeks.

3.3. RoB. Table 2 presents a summary of the RoB assessment results. Among the three parallel RCTs included in our study, one demonstrated a low RoB [34], whereas the other two had some concerns in terms of RoB. Specifically, the RCT by Li et al. did not describe the allocation concealment methods [33] and that by Wood et al. did not clarify the allocation concealment methods and prespecified plans [32].

Among the five crossover RCTs, one had a low RoB [35], three had some concerns in terms of RoB [17, 24, 31], and one had a high RoB [16]. Three of the five RCTs did not report the allocation concealment methods [16, 17, 24]. Two of the five RCTs provided no information on patients' baseline characteristics after randomization [17, 24]. Three of the five RCTs did not include a washout period or ensured an adequate interval to eliminate carryover effects before outcome measurement [16, 24, 31]. In the RCT by Antonicelli et al., neither participants nor outcome assessors were blinded to the interventions [16]. Furthermore, four of the five RCTs did not describe the prespecified plan [16, 17, 24, 31]. Tables S6–S13 present additional details regarding the RoB assessment results.

3.4. Primary Outcome

3.4.1. Symptoms. All eight RCTs assessed symptom scores for both intervention and control groups [16, 17, 24, 31–35]. Three RCTs used the total nasal symptom score (TNSS), which helps assess various nasal symptoms, such as itchy nose, sneezing, runny nose, and stuffy nose [31, 32, 34]. The remaining five RCTs used the total symptom score (TSS), which helps assess nasal symptoms as well as additional conditions, such as itchy eyes, ears, and throat [17, 24, 33]; eye redness and tearing [33, 35]; cough and dyspnea [16]; asthma [17]; and medication use [17, 24]. Furthermore, four RCTs reported symptom scores calculated for the whole day [16, 17, 33, 34], and the remaining RCTs reported symptom scores calculated separately for the daytime and nighttime [24, 31, 32, 35]. A pooled analysis showed significantly lower nighttime symptom scores (SMD = −0.21; CI: −0.35 to −0.07 in the FEM and −0.35 to −0.08 in the REM;

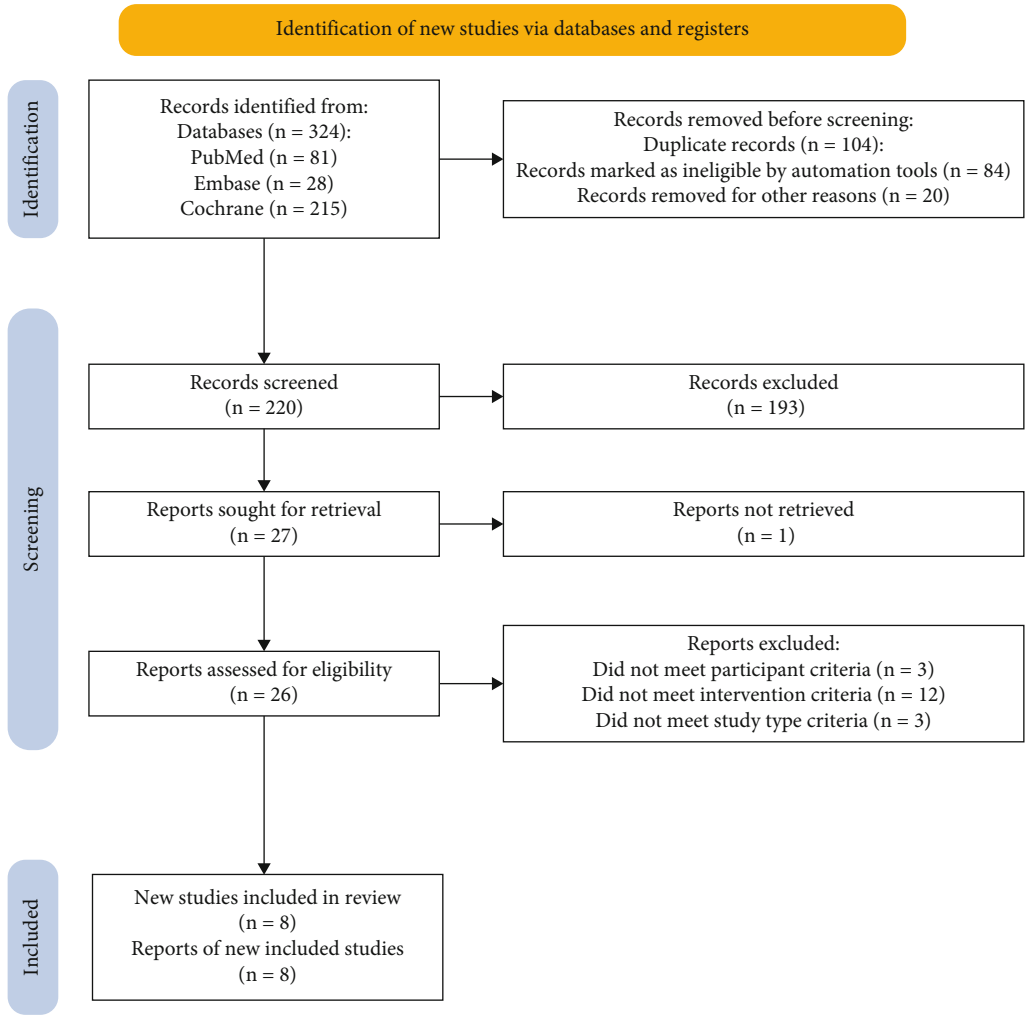


Figure 1: Flow diagram of the search process and search results.

Figure 2(a)). Another pooled analysis indicated significantly lower daytime symptom scores (SMD = −0.16; 95% CI: −0.30 to −0.03 in both FEM and REM; Figure 2(b)).

3.5. Secondary Outcome

3.5.1. Medication Use. Three of the included RCTs reported daily medication use. The RCT conducted by Wood et al. reported medication scores separately for maintenance and as-needed medication use [32]. The other two RCTs reported medication scores without specifying whether they related to maintenance or as-needed medication use [17, 34]. Figure 3(a) presents the results of a pooled analysis conducted using medication scores extracted from the RCT of Reisman et al. and Park et al. along with as-needed nasal medication scores extracted from that of Wood et al. This analysis revealed nonsignificantly reduced medication scores (SMD = −0.08; 95% CI: −0.34 to 0.18 in the FEM, 95% CI: −0.55 to 0.39 in the REM). Figure 3(b) presents the results of a pooled analysis conducted using medication scores extracted from the RCT of Reisman et al. and Park et al. along with maintenance nasal medication scores extracted from that of Wood et al. This analysis also indicated that medication scores did not show significant reduction (SMD = −0.05; 95% CI: −0.31 to 0.20 in the FEM, 95% CI: −0.34 to 0.24 in the REM).

3.5.2. QoL. Three of the included RCTs involved the administration of the Rhinoconjunctivitis Quality of Life Questionnaire [33, 34] and that of the Nocturnal Rhinoconjunctivitis Quality of Life Questionnaire [35] for QoL assessment. Figure 4 presents the results of a pooled analysis conducted using these outcomes, which showed the QoL was not significantly decreased (SMD = −0.12; 95% CI: −0.35 to 0.11 in the FEM and SMD = −0.06; 95% CI: −0.81 to 0.68 in the REM).

3.5.3. PEFR. Three of the included RCTs used PEFR as a measure of the degree of airway obstruction in patients with AR [16, 31, 32]. A pooled analysis using PEFR data revealed no significant increase in PEFR in patients with AR when using air filters (SMD = 0.03; 95% CI: −0.20 to 0.26 in the FEM and −0.18 to 0.24 in the REM; Figure 5).

Table 1: Characteristics of included trials.

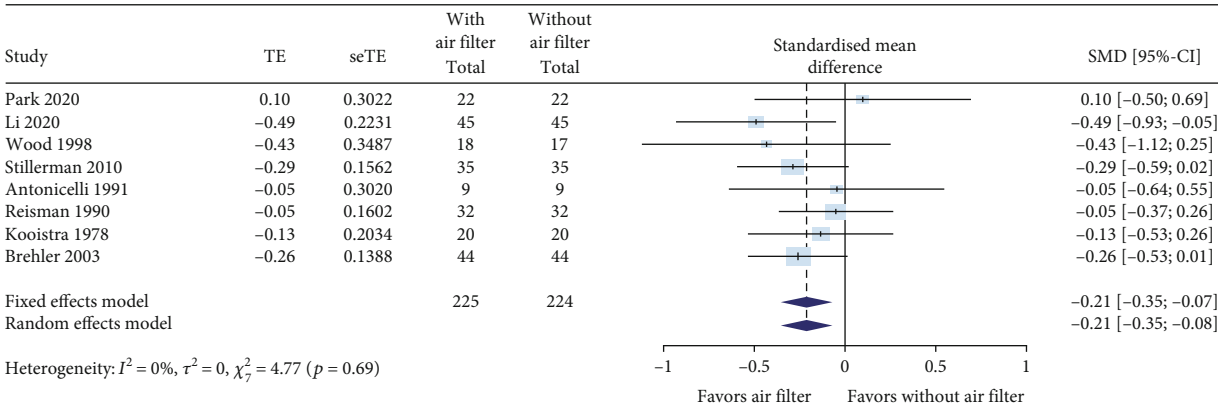
Study (year), country	Design	AR type	Size (M/F)	Age (years)	Intervention and control	Operating time/day and study period
Park et al. [34], South Korea	RCT parallel	AR sensitized to HDMs	I: 22 (6/16) C: 22 (9/13)	I: 35.68 ± 10.55 C: 33.27 ± 8.91	I: air purifier with HEPA filter C: without HEPA filter	24 hours/day 6 weeks
Li et al. [33], China	RCT parallel	AR sensitized to *Artemisa* pollen	I: 45 (24/21) C: 45 (26/19)	I: 35.53 C: 36.11	I: air purifier with HEPA filter C: placebo HEPA filter	Continuous 8 weeks (4 weeks for treatment and 4 weeks for observation)
Wood et al. [32], USA	RCT parallel	AR sensitized to cat allergen	I: 18 (2/16) C: 17 (8/9)	I: 36.3 C: 36.4	I: air cleaner with HEPA filter C: without HEPA filter	Continuous 3 months
Brehler et al. [31], Germany	RCT crossover	AR sensitized to tree or grass pollen	44 (23/31)	NI	I: air ventilator with pollen filter C: placebo filter	Continuous 4 weeks (2 weeks for intervention and 2 weeks for control)
Stillerman et al. [35], USA	RCT crossover	PRAC sensitized to dust, mite, dog, or cat	35 (13/22)	39.1	I: PAF pillow with HEPA filter C: blocked HEPA filter	During sleep (at least 12 of 14 nights) 6 weeks (2-week treatment, 1-week wash out, 2-week treatment, 1-week washout)
Antonicelli et al. [16], Italy	RCT crossover	AR sensitized to *D. pteronyssinus* and *D. farina*	9 (NA)	16	I: air cleaner with HEPA filter C: without filter	24 hours/day 16 weeks (8 weeks for treatment and 8 weeks for observation)
Reisman et al. [17], USA	RCT crossover	Perennial AR sensitized to HDMs	32 (12/20)	27.5	I: air cleaner with HEPA filter C: placebo filter	NI 8 weeks (4 weeks for intervention and 4 weeks for control)
Kooistra et al. [24], USA	RCT crossover	AR sensitized to ragweed pollen	20 (11/9)	NI	I: air cleaner with internal filter C: no filter	24 hours/day 8 weeks (4 weeks for intervention and 4 weeks for control)

AR: allergic rhinitis; C: control; F: female; HDMs: house dust mites; HEPA: high-efficiency particulate air; I: intervention; M: male; NA: not applicable; NI: no information; PAF: personal air filtration; PRAC: perennial allergic rhinoconjunctivitis; RCT: randomized controlled trial.

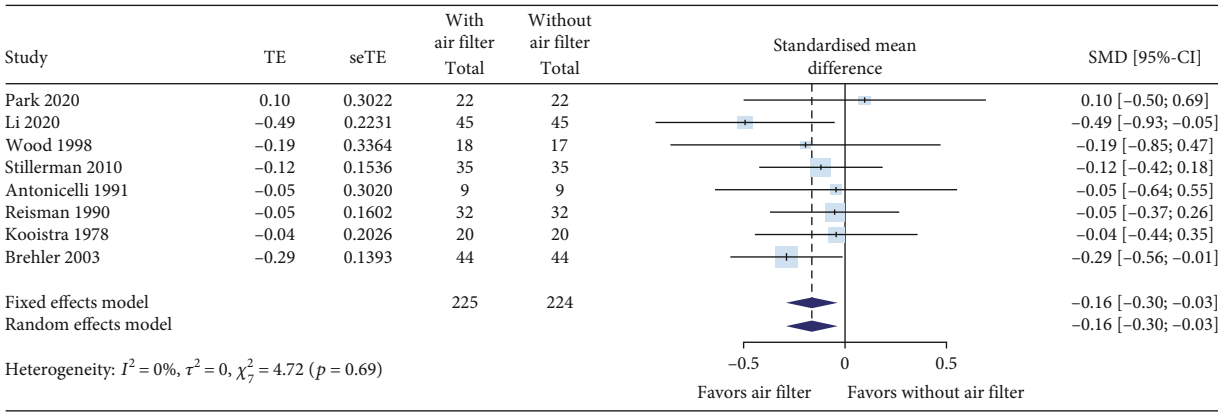
Table 2: Summary of the risk of bias.

Study	Year	Study design	D1	DS	D2	D3	D4	D5	Overall
Park et al. [34]	2020	RCT parallel	Low		Low	Low	Low	Low	Low
Li et al. [33]	2020	RCT parallel	Some concerns[†]		Low	Low	Low	Low	Some concerns
Wood et al. [32]	1998	RCT parallel	Some concerns[†]		Low	Low	Low	Some concerns[‡‡]	Some concerns
Brehler et al. [31]	2003	RCT crossover	Low	Some concerns[§]	Low	Low	Low	Some concerns[‡‡]	Some concerns
Stillerman et al. [35]	2010	RCT crossover	Low	Low	Low	Low	Low	Low	Low
Antonicelli et al. [16]	1991	RCT crossover	Some concerns[†]	Some concerns[§]	Some concerns[¶]	Low	High[††]	Some concerns[‡‡]	High
Reisman et al. [17]	1990	RCT crossover	Some concerns[†,‡]	Low	Low	Low	Low	Some concerns[‡‡]	Some concerns
Kooistra et al. [24]	1978	RCT crossover	Some concerns[†,‡]	Some concerns[§]	Low	Low	Low	Some concerns[‡‡]	Some concerns

D1: randomization process; DS: bias arising from period and carryover effects; D2: deviations from the intended interventions; D3: missing outcome data; D4: measurement of the outcome; D5: selection of the reported result. [†]Lack of description of the allocation concealment methods. [‡]Lack of baseline information of two groups after randomization. [§]Lack of washout period. Lack of sufficient time passes before outcome measurement in the second period for any carryover effects to have disappeared. [¶]Participants aware of their assigned intervention during each period of the trial. [††] Outcome assessors aware of the intervention received by study participants and influenced by knowledge of intervention received. [‡‡]Lack of prespecified plans.



(a)



(b)

Figure 2: (a) Forest plot of symptom scores pooled with nighttime symptom scores from the studies by Wood et al., Stillerman et al., Kooistra et al., and Brehler et al. and whole-day symptom scores from the remaining studies. (b) Forest plot of symptom score pooled with daytime symptom scores from the studies by Wood et al., Stillerman et al., Kooistra et al., and Brehler et al. and whole-day symptom scores from the remaining studies.

3.6. Sensitivity Analysis. We performed sensitivity analyses after removing the data obtained from the RCT conducted by Kooistra et al. [24] and assuming that the correlation coefficient between the experimental and control periods in crossover RCTs was 0 or approximately 1. The results of the analyses consistently indicated that the air filters reduced the symptom scores of patients with AR (Figures S1–S6).

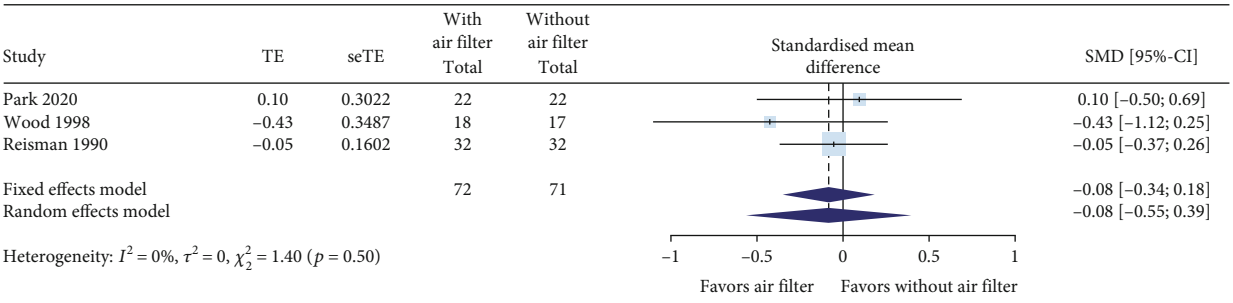
3.7. Subgroup Analysis. To explore potential variations in the effects of air filters on AR symptoms, we conducted subgroup analyses by using data pertaining to symptom scores, allergen types, study designs, air filter devices, and funding. The differences between the TNSS and TSS in the effects of air filters on symptom scores were nonsignificant (Figures S7 and S8). Moreover, the differences among allergen types were nonsignificant (Figures S9 and S10). Furthermore, no significant differences in the effects of air filters on AR symptoms were observed between the parallel and crossover designs (Figures S11 and S12) or among the types of air filter devices (Figures S13 and S14). Funding exerted no significant effect on changes in AR symptoms with air filters (Figures S15 and S16).

3.8. Meta-regression. We conducted meta-regression analyses to evaluate the effects of certain covariates on AR symptoms (Figures S17–S19). No significant association was noted between symptom improvement and publication year (coefficient: −0.0059; $p = 0.211$). Furthermore, no significant association was found between lower symptom scores and longer study periods (coefficient: 0.0097; $p = 0.728$) or between lower symptom scores and higher latitudes (coefficient: −0.0065, $p = 0.567$).

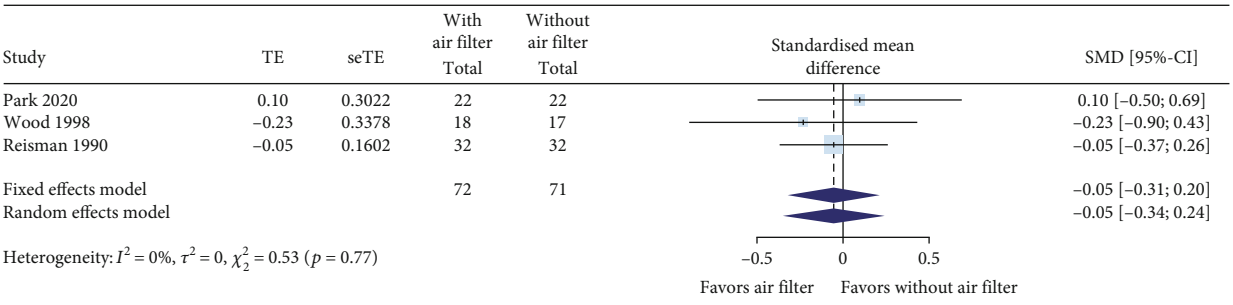
3.9. Publication Biases. Funnel plots revealed no apparent asymmetry among the symptom scores derived from the included RCTs, indicating no publication bias in the reporting of RCT results (Figure S20 and S21).

4. Discussion

To the best of our knowledge, this is the first systematic review and meta-analysis to provide insights into the benefits of air filters for patients with AR. Our main finding indicated that the use of air filters reduced symptom scores but did not reduce medication use, enhance QoL, or improve PEFR in patients with AR.



(a)



(b)

Figure 3: (a) Forest plot of medication use pooled with as-needed medication use scores from the study by Wood et al. and medication scores from the studies of Reisman et al. and Park et al. (b) Forest plot of medication use pooled with maintain medication use scores from the study by Wood et al. and medication scores from the studies of Reisman et al. and Park et al.

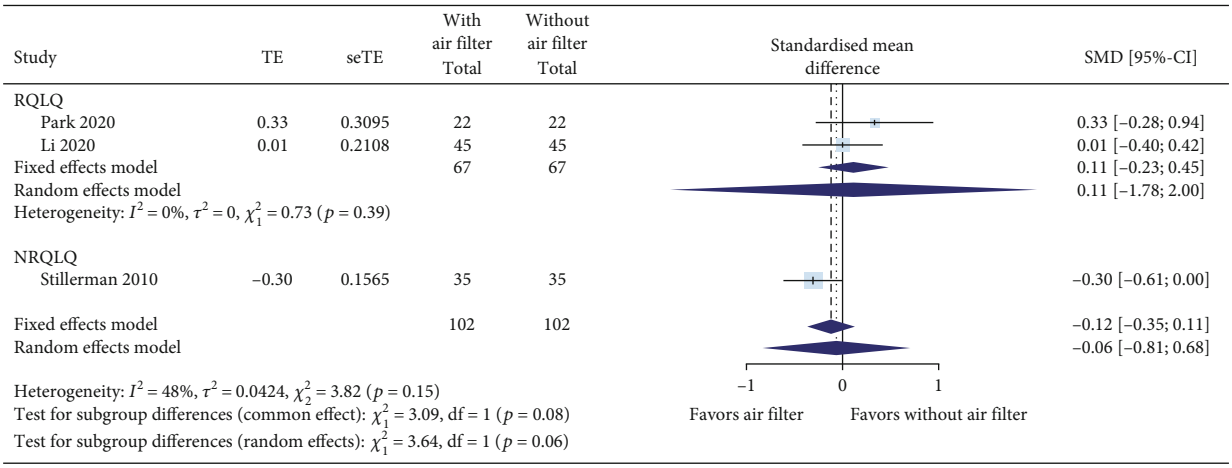


Figure 4: Forest plot of quality of life.

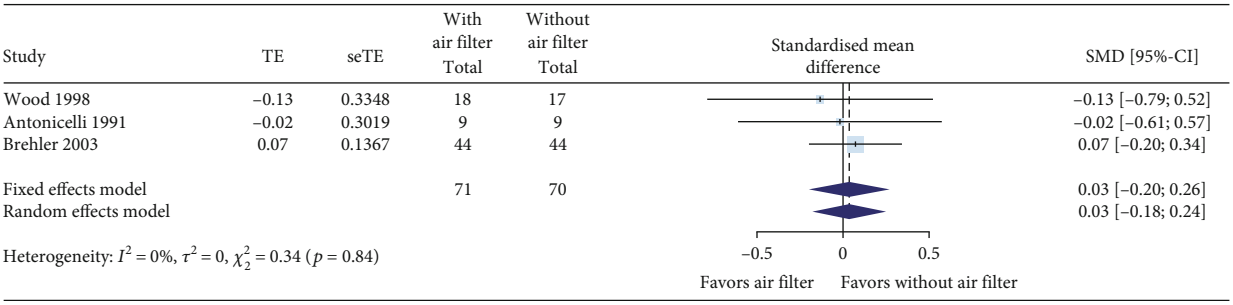


Figure 5: Forest plot of peak expiratory flow rate.

AR symptoms are often induced by exposure to allergen levels that exceed certain thresholds [36, 37]. Such exposure triggers a series of inflammatory responses, including the presentation of allergens by antigen-presenting cells to CD4+ T lymphocytes, resulting in the production of interleukin- (IL-) 4, IL-5, IL-13, and other cytokines secreted by T helper 2 cells [38]. These cytokines drive proinflammatory responses; interact with B lymphocytes; produce immunoglobulin E antibodies against allergens through mucosal infiltration; and activate plasma cells, mast cells, and eosinophils [39]. Notably, exposure to particulate matter (PM) may exacerbate the immune response to allergens, thereby resulting in severe nasal symptoms in individuals with AR, particularly in those residing in areas with elevated levels of air pollution [40, 41]. Air filters help reduce allergen exposure by effectively regulating the levels of pollens, HDMs, pet allergens, and PM in indoor environments [42, 43] and thus alleviate inflammation reactions and ameliorate AR symptoms [15].

Several validated patient-reported outcome measures (PROMs), such as the TNSS and visual analogue scale score [44–46], or self-defined PROMs, such as the TSS, have been used to measure disease burden in various domains of AR. PROMs serve as valuable tools for evaluating disease severity in patients with AR [47]. The TNSS is calculated on the basis of the total score for four typical nasal symptoms of AR, namely, sneezing, rhinorrhea, nasal itching, and nasal obstruction, which can provide a modest correlation with peak nasal inspiratory flow [48]. Accordingly, previous systematic reviews have used the TNSS to evaluate the efficacy of various interventions, such as medication or probiotic use, against AR [49, 50]. Moreover, observational studies have used the TNSS to explore the benefits of air filters for patients with allergies. These studies have consistently reported significant and sustained amelioration of allergy symptoms [19, 51]. Bergmann et al. also observed that the use of air filters resulted in significant improvements in the TNSSs of patients with AR or pollen allergy [52]. The TNSS was used in three RCTs included in our meta-analysis; the pooled results indicated that air filters may ameliorate nasal symptoms associated with AR [31, 32, 34]. Although our subgroup analyses revealed no significant differences between the TNSS and TSS, this finding should be interpreted cautiously because the included RCTs reported TSSs for various subdomains of AR. The TSS used in some studies was calculated on the basis of the scores for AR-related nasal, eye, and respiratory symptoms [16, 17, 33, 35], which made it difficult for us to assess the severity of AR symptoms in a specific organ system. Other studies have included scores for other subdomains such as medication use and asthma into the TSS [17, 24], further complicating the assessment of AR symptoms. According to the findings of previous studies and the results of our pooled analyses, the use of air filters may not reduce medication use in patients with allergic respiratory diseases [19, 53]. Li et al. demonstrated that the presence of asthma does not influence the severity of AR symptoms [46]. Therefore, to minimize interference from various subdomains, specific and validated measures should be developed for assessing AR symptoms in specific organs after interventions involving the use of air filters.

The efficacy of an air filter depends on the balance between filtration efficiency, airflow, and dust-holding capacity [54]. Regarding filtration efficiency, HEPA filters can reduce allergen concentrations by approximately 65%–90% [43, 55]. In terms of airflow, an increased airflow rate is more strongly associated with reduced concentrations of cat, dust, and mite allergens than an increased filtration efficiency [56]. Kim and Yeo indicated that high airflow rates are more effective than high filtration efficiency in reducing indoor $PM_{2.5}$ levels, particularly under conditions characterized by low outdoor $PM_{2.5}$ generation and high indoor $PM_{2.5}$ generation [57]. Regarding dust-holding capacity, changing filters in a timely manner is essential. Dirty filters lower filtration ability and may become a source of allergens, thereby increasing the risk of allergic respiratory symptoms [58, 59]. Among the RCTs included in our study, three reported that HEPA filters could remove 43.3%–73.4% of allergens or PM in the study environment [17, 32, 34] and one reported that the use of pillows equipped with filters led to a 99.99% reduction in particle concentration within the breathing zone [35]. However, none of these four RCTs provided any information on the frequency of filter replacements; only two [17, 32] RCTs provided airflow-related information. Therefore, determining the contribution of each of these factors to the reduction of allergen concentrations was challenging. Nevertheless, the extent of air filter-mediated improvements in AR symptoms was higher in more recent studies, indicating the gradual advancement of the air filtration technology. In addition to the finding related to potential gradual improvements in the configuration of air filters, a notable insight was offered by Li et al. [33] In their study, participants were instructed to spend more than 8 hours per day in their bedrooms, a detail not mentioned in any other study. Furthermore, the air purifiers were used continuously every day. Under these conditions, the participants of the included studies might have been exposed to significantly low levels of allergens, which might have led to a reduction in the severity of rhinitis symptoms [60]. Further research in this area may help identify factors influencing the improvement of AR symptoms.

AR can be induced by a wide range of allergens that may lead to symptoms of varying severity. HDMs and pet allergens are common indoor irritants that may cause perennial AR [61]. Pollens and spores are mainly outdoor allergens that may contribute to seasonal AR [62]. A systematic review reported that patients with seasonal AR often experience significantly more severe nasal symptoms than do those with perennial AR [46]. Stillerman et al. indicated that patients with AR who experienced moderate to severe nasal symptoms exhibited elevated levels of improvements after filter interventions [35]. The findings of our subgroup analysis corresponded to the aforementioned findings in which AR patients with pollen sensitization had a relatively lower SMD on symptom scores compared to AR patients with HDMs and pets sensitization after the application of air filters. These discrepancies may be attributable to the following reasons. First, allergens vary in size and properties [13]. Large allergens, such as pollens or spores, tend to deposit in the nasal cavity, leading to nasal and ocular symptoms. In contrast, small allergens, such as HDMs and pet allergens, tend to deposit in the airways, potentially causing asthma

[63]. Second, the concentrations of pollens or spores are higher in outdoor environments than in indoor environments [64, 65]. During clinical trials involving air filter interventions, patients with AR who are sensitive to such allergens were required to stay indoors while receiving the interventions; this regulation ensured a relatively low level of exposure to outdoor allergens. Third, in the indoor environment, larger particles tend to settle more rapidly and may not reach the air filters, which reduces their removal efficiency. However, smaller particles measuring less than 0.1 μm in size can still be effectively trapped by HEPA filters through processes such as diffusion trapping, which results from Brownian motion [13, 66, 67]. Fourth, human activities that alter vegetation have led to variations in the concentrations of outdoor allergens, including pollen [33]. In cases where there is no barrier between indoor and outdoor spaces, a correlation exists between outdoor and indoor pollen levels, with higher outdoor concentrations leading to higher indoor levels [68]. Consequently, during the peak pollen season, indoor pollen concentrations may increase due to this correlation. Therefore, allergen avoidance through air filters alone may not be sufficient to ameliorate various AR symptoms. To effectively manage AR symptoms, a combination of strategies may be necessary. These strategies can include removing carpets [69]; reducing upholstered furniture [70]; using allergen-proof mattresses and pillow covers [71]; cleaning the house regularly through vacuuming and wiping [72]; maintaining appropriate indoor humidity levels [73]; closing windows during pollen seasons; [74] and washing bedding, curtains, and pets at regular intervals [75, 76].

Through this study, we have discovered some understudied areas, mainly in symptoms assessment and estimating missing data. In terms of symptom assessment, existing studies on air filters for AR predominantly utilize the TNSS to assess nasal symptoms. Although the RQLQ encompasses symptoms beyond nasal issues, only the study by Li et al. [33] included the detailed subdomains, making it challenging to understand changes in other symptoms. The development of additional scoring systems, such as the total ocular symptom score [77], could assist healthcare professionals in achieving a more comprehensive understanding of improvements in AR. For the other understudied issue, the missing data, we employed assumptions from previous studies to estimate the SD. There are numerous studies exploring methods for calculating missing SDs [78]. For instance, the method introduced by Walter and Yao in 2007 can be utilized to estimate the SD when the dataset includes the minimum and maximum values or ranges [79]. Moreover, in 2014, Wan et al. published a calculating program to solve the problem of missing SD when the available data comprises a median, lower quartile, and upper quartile [80]. Some methods require expertise and are currently unavailable in standard meta-analysis software, limiting accessibility for the majority of systematic reviewers. Therefore, experts consistently improve the missing data conversion process [81], allowing systematic reviewers to obtain the maximum information from included studies when original data is inaccessible.

From the statistical perspective, our findings show that there is no significant heterogeneity among the included RCTs. However, potential heterogeneity may exist among the trials because of differences in clinical situations. First, age and disease severity varied among the included RCTs. Older patients may experience milder AR symptoms [82]. Second, the patients' residence locations varied across the included RCTs. Climatic differences, including differences in latitude, altitude, and humidity, may affect the severity of AR symptoms [83, 84]. Patients with more severe symptoms showed greater improvement following air filter interventions [35]. Third, the operation duration, configuration, and location of the air filter devices varied across the RCTs, resulting in varying levels of particle removal efficiency [60]. Longer operation durations and higher airflow rates can more effectively reduce the concentrations of allergens. Additionally, placing these devices in close proximity to individuals, such as on the bed headboard while sleeping, can further reduce particle concentrations and alleviate allergic reactions. Fourth, some RCTs used different assessment tools to measure AR symptoms or QoL. These assessment tools may encompass distinct subdomains and measure different aspects of AR, potentially leading to disparities between the measured and intended concepts as well as variations in reliability and validity, thereby yielding inaccurate or imprecise measurement outcomes [85].

This study has some limitations. First, our meta-analysis had a relatively small sample size; this might have limited the generalizability of our findings and reduced the statistical power of our results. Second, the reviewed clinical trials rarely included children. Consequently, we could not comprehensively analyze the efficacy of air filters in managing AR symptoms in the pediatric population. Third, while most RCTs concentrated on the efficacy of air filters against a single type of allergen, it is worth noting that in real-life situations, individuals with AR may be simultaneously allergic to multiple allergens. Fourth, the included studies did not provide comprehensive information on the characteristics of the air filters used. Fifth, some crossover RCTs did not include a washout period between the intervention and control phases, which might have introduced carryover effects, potentially underestimating the effects of the intervention [27, 86]. Sixth, the actual SD values could not be determined for the trial conducted by Kooistra et al. [24] Finally, the correlation coefficient could be derived from only one study. Therefore, to strengthen our analysis, we performed sensitivity analyses by using various assumed coefficients [27].

5. Conclusion

According to our systematic review and meta-analysis, air filters may help alleviate AR symptoms, but they do not have significant effects on the medication use, QoL, or PEFR. Factors such as allergen type, air filter device, symptom scores, study design, funding, study duration, publication year, and geographic latitude did not influence the effectiveness of air filters in mitigating AR symptoms. Additional high-quality studies are warranted to confirm the benefits of air filters for patients with AR.

Data Availability

The data presented in this manuscript were obtained from the previously published studies; pertinent information has been included in the manuscript.

Additional Points

Practical Implications. (1) To the best of our knowledge, this is the first meta-analysis to investigate the benefits of air filters for patients with allergic rhinitis (AR). (2) Patients with AR may find relief from AR symptoms by using air filters. However, the use of these filters appears to have no significant effect on medication use, quality of life, or peak expiratory flow rate.

Conflicts of Interest

The authors declare no potential conflicts of interest relevant to this study.

Authors' Contributions

M.Y.S. designed this study, extracted and analyzed the data, and drafted the manuscript. H.W.H, S.Y.C., and M.J.S. analyzed the data and performed the calculations. W.C.L. and C.C. participated in the critical interpretation of the data and the revision of the manuscript.

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Supplementary Materials

Table S1: PRISMA 2020 checklist. Table S2: keywords and search strategy in the PubMed. Table S3: keywords and search strategy in the Embase. Table S4: keywords and search strategy in the Cochrane Library. Table S5: excluded studies and reasons. Table S6: comprehensive information on the risk of bias in Park et al.'s study. Table S7: comprehensive information on the risk of bias in Li et al.'s study. Table S8: comprehensive information on the risk of bias in Wood et al.'s study. Table S9: comprehensive information on the risk of bias in Brehler et al.'s study. Table S10: comprehensive information on the risk of bias in Stillerman et al.'s study. Table S11: comprehensive information on the risk of bias in Antonicelli et al.'s study. Table S12: comprehensive information on the risk of bias in Reisman et al.'s study. Table S13: comprehensive information on the risk of bias in Kooistra et al.'s study. Figure S1: forest plot of symptom score pooled with nighttime symptoms after removing the study by Kooistra et al. The SMD was −0.22 in both FEM (95% CI: −0.37 to −0.08) and REM (95% CI: −0.38 to −0.06). Figure S2: forest plot of symptom score pooled with daytime symptoms after removing the study by Kooistra et al. The SMD was −0.18 in both FEM (95% CI: −0.32 to −0.03) and REM (95% CI: −0.33 to −0.03). Figure S3: forest plot of symptom score pooled with nighttime symptoms by assuming the correlation coefficient between the experimental and control periods in crossover studies was 0. The SMD was −0.23 in both FEM (95% CI: −0.42 to −0.04) and REM (95% CI: −0.40 to −0.07). Figure S4: forest plot of symptom score pooled with daytime symptoms by assuming the correlation coefficient between the experimental and control periods in crossover studies was 0. The SMD was −0.19 in both FEM (95% CI: −0.37 to 0.00) and REM (95% CI: −0.35 to −0.02). Figure S5: forest plot of symptom score pooled with nighttime symptoms by assuming the correlation coefficient between the experimental and control periods in crossover studies was 0.99. The SMD was −0.19 in FEM (95% CI: −0.19 to −0.18) and −0.17 in REM (95% CI: −0.28 to −0.05). Figure S6: forest plot of symptom score pooled with daytime symptoms by assuming the correlation coefficient between the experimental and control periods in crossover studies was 0.99. The SMD was −0.14 in FEM (95% CI: −0.15 to −0.13) and -0.12 in REM (95% CI: −0.23 to −0.02). Figure S7: forest plot of subgroup analysis of symptom score pooled with nighttime symptoms in different symptom scores. Subgroup differences between TNSS and TSS were not significant in both FEM ($p = 0.88$) and REM ($p = 0.86$). Figure S8: forest plot of subgroup analysis of symptom score pooled with daytime symptoms in different symptom scores. Subgroup differences between TNSS and TSS were not significant in both FEM ($p = 0.58$) and REM ($p = 0.51$). Figure S9: forest plot of subgroup analysis of symptom score pooled with nighttime symptoms in different allergen types. Subgroup differences between indoor allergens (e.g., HDMs or pets) and outdoor allergens (e.g., pollen) were not significant in both FEM ($p = 0.38$) and REM ($p = 0.28$). Figure S10: forest plot of subgroup analysis of symptom score pooled with daytime symptoms in different allergen types. Subgroup differences between indoor allergens (e.g., HDMs or pets) and outdoor allergens (e.g., pollen) were not significant in both FEM ($p = 0.16$) and REM ($p = 0.09$). Figure S11: forest plot of subgroup analysis of symptom score pooled with nighttime symptoms in different study design. Subgroup differences between parallel design and crossover design were not significant in both FEM ($p = 0.47$) and REM ($p = 0.55$). Figure S12: forest plot of subgroup analysis of symptom score pooled with daytime symptoms in different study design. Subgroup differences between parallel design and crossover design were not significant in both FEM ($p = 0.48$) and REM ($p = 0.58$). Figure S13: forest plot of subgroup analysis of symptom score pooled with nighttime symptoms in different air filter devices. Subgroup differences between air purifier/air cleaner, PAF pillow, and air ventilator were not significant in both FEM ($p = 0.72$) and REM ($p = 0.70$). Figure S14: forest plot of subgroup analysis of symptom score pooled with daytime symptoms in different air filter devices. Subgroup differences between air purifier/air cleaner, PAF pillow, and air ventilator were not significant in both FEM ($p = 0.59$) and REM ($p = 0.58$). Figure S15: forest plot of subgroup analysis of symptom score pooled with nighttime symptoms with or without funding. Subgroup differences between funding and no funding were not significant in both FEM ($p = 0.38$) and REM ($p = 0.28$). Figure S16: forest plot of subgroup analysis of symptom score pooled with daytime symptoms with or without funding. Subgroup differences between funding and no funding were not significant in both FEM ($p = 0.16$) and REM ($p = 0.09$). Figure S17: meta-regression on published year. The coefficient was −0.0059 with a p value of 0.211.

Figure S18: meta-regression on study periods (weeks). The coefficient was 0.0097 with a p value of 0.728. Figure S19: meta-regression on latitude. The coefficient was −0.0065 with a p value of 0.567. Figure S20: the funnel plot in primary outcome calculated from nighttime symptom score of included trials. The p value of the Egger's test was 0.817, indicating no potential publication bias. Figure S21: the funnel plot in primary outcome calculated from daytime symptom score of included trials. The p value of the Egger's test was 0.631, indicating no potential publication bias. *(Supplementary Materials)*

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