A Systematic Review of Indoor Air Quality Interventions and Childhood Asthma

Wellesley Institute
advancing urban health

September, 2016

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Introduction

The household environment is an essential determinant of health (Public Health Agency of Canada, 2013). The health impacts of poor quality housing on children are well known and the city of Toronto could take significant steps to improve housing quality for child health.

Children with asthma are the most vulnerable to the effects of poor indoor air quality (Ministry of Health and Long-Term Care, 2013). Asthma is the most common childhood chronic disease, with approximately 13 percent of children in Ontario diagnosed with the condition (MOHLTC, 2013). Living with childhood asthma is associated with disability, school absences, and poor academic performance (MOHLTC, 2013). Childhood asthma incurs huge costs to Ontario's health care system, accounting for one-third of the total OHIP expenditure (Institute for Clinical Evaluative Sciences, 2006).

Living in substandard housing can increase child asthma symptoms and the related use of health care services. Deteriorating homes or homes kept in poor repair are full of indoor air allergens, such as mold, rodents, house dust mites, and cockroaches. Other factors like smoke and pet hair can further exacerbate asthma symptoms. There is evidence that these allergens play an important role in asthma development and exacerbation. (Lin, Jones, Munsie, et al., 2012; Belanger, Beckett, Triche, et al., 2003; Rauh, Chew, & Garfinkel, 2002).

Low-income families are more likely to live in substandard housing with higher amounts of indoor air allergens (Kitch, Chew, Burge et al., 2000). In Toronto, one in two low-income families live in aged buildings that are in unstable condition (Paradis et al., 2013). Higher childhood asthma morbidity among low-income children could increase child health inequities in Toronto.

There is a need to understand how to improve indoor air quality for low-income asthmatic children. A number of studies have evaluated the impact of indoor air quality interventions on asthma morbidity in a variety of settings. However, no focused systematic review has been conducted to measure the impact of home-based indoor air quality on asthmatic children. This systematic review of peer-reviewed literature focuses on identifying which home-based indoor air quality interventions have shown to reduce asthma morbidity among low-income children.

Methods

Adapting a methodology based on the work of Khan et al. (2003), this review was developed using the five steps to conducting a systematic review. These steps include: 1) framing questions for a review, 2) identifying relevant work, 3) assessing the quality of studies, 4) summarizing the evidence, and 5) interpreting the evidence.

Criteria for study selection

This review included studies that measured the impact of interventions on children younger than 18 years of age, from low-income households (as identified by their community's low-income cut off point), and living in urban or suburban neighbourhoods. To meet the criteria for inclusion in this review, interventions had to reduce indoor air allergens that exacerbate asthma (mold, smoke, rodents, cockroaches, pet dander, and house dust mites). The effects of these interventions were compared with either "no intervention" or "medical advice only" intervention scenarios. Only clinical asthma morbidity outcomes were included in this review. These outcomes included: 1) asthma symptoms (coughing, wheezing, shortness of breath, tightness in chest, sleep limitations, activity restrictions, and asthma attacks), 2) uncontrolled asthma, and 3) asthma-related health care usage (emergency department [ED] visits, hospitalization, and clinic visits). Asthma incidences falling outside these parameters were considered out of scope and were thus excluded (refer to Appendix A for a rationale of these criteria).

Data collection and analysis

Search Strategy

A search strategy was developed in collaboration with a librarian from Gerstein Library at the University of Toronto. I searched the following eight databases for studies regarding indoor air quality and asthma among children: BIOSIS, CINAHL, Cochrane, EMBASE, Medline, PAIS, PubMed, and SCOPUS. Limits were imposed for publishing year (2000 onwards), language (English), and age (0-18 years). There were no limits on other characteristics of participants, study design, or location. I did not restrict the search to only interventions of indoor air quality, and instead kept the search more general to avoid missing studies that would not be retrieved with the use of "intervention" as the keyword (refer to Appendix B for database-specific search strategies). One reviewer (DK) screened the titles and abstracts of studies for inclusion.

Data extraction

Data from included studies were manually extracted and summarized into tables (refer to Appendix C for a summary of findings table). This process included tracking descriptive data about the setting, population, sample size, measurement tools, type of analysis, and any changes in post-intervention outcome. For each included study, one (DK) reviewer extracted data.

Quality assessment

The methodological quality of the intervention studies was assessed using a Quality Assessment Tool for Quantitative Studies by the Effective Public Health Practice Project. Through this tool, I assessed selection bias, study design, confounders, blinding, data collection methods, withdrawals, and dropouts. For each included study, one reviewer (DK) assessed the quality of included articles (refer to Appendix D for the risk of bias assessment table).

Data synthesis

The studies were too heterogeneous (varied by population groups, outcomes, follow-up times, etc.) to permit meta-analysis (pooling of statistical results). Instead, for each intervention subcategory we summarized data into two classifications—studies and effect measures that showed significant change in asthma morbidity (i.e. with an effect at $p<0.05$) and studies and effect measures that showed no significant change in asthma morbidity (i.e. with an effect at $p>0.05$). I narratively described the evidence for each outcome according to whether studies were supporting or not supporting a positive change.

Findings

Description of included studies

This review included 21 studies (refer to Appendix E for a flow chart of study inclusion/exclusion). Out of the 21 articles, 10 were randomized control trials (RCTs) and 11 were prospective cohort studies (refer to Appendix F for hierarchy of evidence pyramid). Follow-up periods of included studies ranged from five to 28 months. There were 17 studies conducted in the United States, one in Canada, one in the United Kingdom, one in New Zealand, and one in Japan.

Types of indoor air quality interventions found in the review

The two types of indoor air quality interventions found in this review aimed to reduce one or more sources of indoor air allergens that exacerbate asthma and include: 1) multi-trigger (54.5%) and 2) single-trigger interventions (45.5%).

Multi-trigger interventions included activities that reduced exposure to two or more environmental triggers that exacerbate asthma. All multi-trigger interventions were delivered through multiple components which included:

- Home visits by lay community health workers or trained professionals
- In-home environmental assessment to gauge the air quality in homes
- Clinical asthma management and/or home environmental trigger-reduction education
- Minor remediation, which included provision of allergen-impermeable bedding covers, pest baits, door mats, storage bins, and cleaning supplies
- Moderate remediation, which included providing high-efficiency particle (HEPA) filtration, dehumidifier, vacuum cleaners, filling cracks in walls, installing ventilators, and integrated pest management
- Major remediation, which included mold and moisture reduction, cleaning/repairing gutters, removing water damaged building materials, removal of carpets, alterations to heating and other customized structural interventions

Single-trigger interventions included activities that reduced exposure to one environmental trigger that exacerbates asthma. These included dust mite avoidance counselling, air quality control, pest remediation, mold/moisture remediation, and efficient heating systems. Some single-trigger interventions provided education and home visits, whereas others did not.

Effect of Indoor Air Quality Interventions on Asthma Morbidity among Low-Income Children

Multi-trigger Interventions

The review found 12 multi-trigger interventions that assessed asthma morbidity before and after intervention. All 12 interventions were multicomponent (offered one or more components listed above). Out of the 12 interventions, all offered home visits (100%), in-home environmental assessment (100%), clinical asthma management education (100%), and home environmental trigger-reduction (100%). Eleven offered minor, moderate, and/or major home remediation (92%). Due to differences in the type of remediation offered, results of multi-trigger interventions are presented based on standard remediation categories identified in the review and analyzed per outcome type.

Minor remediation

Three multi-trigger, multicomponent intervention studies evaluated minor remediation (Carrillo et al., 2015; Primomo et al., 2006; Williams et al., 2006). Of these three studies, two were prospective cohort studies (Carrillo et al., 2015; Primomo et al., 2006) and one was an RCT (Williams, 2006). Out of the two cohort studies, one measured asthma symptoms (Carrillo et al., 2015) and both measured health care usage (Carrillo et al., 2015; Primomo et al., 2006). The RCT measured asthma severity scores (Williams et al., 2006).

Two studies found significant reductions in all five measures of asthma symptoms (Carrillo et al., 2015; Williams et al., 2006) (Table 1). One cohort study, rated strong, educated participants on how to keep their homes clean and ventilated and provided allergen-proof mattress and pillow casings. This study found significant reductions in children reporting asthma attacks or trouble breathing ($p=0.00$), symptoms of wheezing or whistling ($p=0.00$), and difficulty sleeping due to asthma ($p=0.00$) (Carrillo et al., 2015). Findings from one RCT, rated weak, provided effective bedding materials, cockroach eradication gel, professional home cleaning, and placement of roach bait. This study highlighted that the functional severity score (which included frequency of wheeze, wake at night with cough/wheeze, wake in morning with wheeze, severe attack, home activities limited, and sports activities limited) improved 25% in the intervention group compared to the control group at 12 months ($p<0.01$) (Williams et al., 2006).

Findings on health care usage were more varied, showing significant improvements in two out of six measures from two cohort studies (Carrillo et al., 2015; Primomo et al., 2006) (Table 1). The cohort study found significant reductions in participants reporting one or more clinic visits ($p<0.05$), but reporting of overnight hospital stays did not reduce significantly (Carrillo et al., 2015). The third study, rated moderate, found significant reductions in children hospitalized ($p<0.01$), but not in unscheduled clinic visits (Primomo et al., 2006). Post-intervention ED visits did not decrease significantly in any of the studies.

Combination of minor and moderate remediation

Five multi-trigger, multicomponent intervention studies evaluated a combination of minor and moderate remediation (Bryant-Stephens et al., 2008; Eggleston et al., 2005; Morgan et al., 2004; Shani et al., 2015). Three of these five studies were RCTs (Bryant-Stephens et al., 2008; Eggleston et al., 2005; Morgan et al., 2004) and two were prospective cohorts (Shani et al., 2015). Out of the three RCTs, two measured asthma symptoms (Morgan et al., 2004; Eggleston et al., 2005), and two reported health care usage (Bryant-Stephens et al., 2008; Morgan et al., 2004). Both of the cohort studies measured asthma control and health care usage (Shani et al., 2015; Turyk et al., 2013).

Findings from two RCTs, one rated strong and the other moderate in quality, showed significant reductions in all seven asthma symptom measures (Morgan et al., 2004; Eggleston et al., 2005) (Table 2). One trial that offered environmental trigger-reduction education, pest baits, cleaning supplies, vacuum cleaners, and effective bedding materials showed significant improvements in days with wheeze ($p=0.00$), waking up at night ($p<0.001$), and delayed or stopped play due to asthma ($p=0.00$) (Morgan et al., 2004). Similarly, the second trial, that offered education along with integrated pest management, allergen-proof bedding, bait traps, and a HEPA filter found that in children with daytime asthma symptoms there was significant reduction at six (p=0.01) and 12 months (p<0.05) (Eggleston et al., 2005). Although there was also a significant decrease in children reporting asthma interference with activity (p<0.05), symptoms with exercise (p<0.01), and nighttime symptoms (p<0.05) at six months, this change was not sustained at 12 months (Eggleston et al., 2005).

Two cohort studies, one rated strong and the other moderate in quality, both offered house dust mite, pest reduction strategies, and comprehensive education. In each study significant reductions in two measures of uncontrolled asthma were measured (Shani et al., 2015; Turyk et al., 2013) (Table 2).

Evidence for health care usage was more varied (Table 2). The results from two RCTs, both rated moderate, showed significant reductions in all measures of ED visits and doctor visits, but not hospitalizations. Findings from one RCT that offered pest baits, cleaning supplies, vacuum cleaners, and effective bedding materials highlighted significant reductions in the number of ED visits (p<0.01), inpatient length of stay (p<0.01), and asthma-related regular sick visits (p<0.05) (Bryant-Stephens et al., 2008). However, the RCT by Morgan et al. (2004) measured a similar intervention and also highlighted reductions in the mean number of unscheduled visits to ED or clinic (P<0.05) but not in the percentage of one or more hospitalizations for asthma (Morgan et al., 2004). The results from two cohort studies, one rated strong and another moderate in quality, showed significant reductions in all measures of ED visits, but reductions in doctor visits and hospitalizations varied. One cohort study found significant reductions in the percentage of child ED visits (p=0.00) and urgent care (p=0.00), as well as hospitalizations (p=0.00) (Turyk et al., 2013). However, the second cohort study found significant reductions only in the number of trips to the ED (p<0.05), and not in overnight hospital stay or visits to doctors (Shani et al., 2015).

Combination of minor, moderate, and major remediation

Four multi-trigger, multicomponent intervention studies evaluated a combination of minor remediation (effective bedding, cleaning supplies), moderate remediation (pest management, dehumidifier, HEPA vacuum), and major remediation (cleaning/repairing gutters, removing mold, installing vents, repairing roofs) (Largo et al., 2011; Polivka et al., 2011; Sweet et al., 2014; Turcotte et al., 2014). All four studies were prospective cohort designs, which measured asthma symptoms and health care usage.

All four cohort studies, two rated strong and two moderate, showed significant reductions in all 13 asthma symptom measures (Largo et al., 2011; Polivka et al., 2011; Sweet et al., 2014; Turcotte et al., 2014) (Table 3). Turcotte et al., (2014) found significant reductions in wheezing episodes (95% CI: 2.7, 5.6), asthma attacks (95% CI: 0.2, 1.0), and difficulty sleeping (95% CI: 4.2, 15.0). Similarly, Largo et al. (2011) found significant reductions in days with wheezing episodes (p=0.00), asthma attacks (p=0.00), shortness of breath (p<0.00), and slowing down or stopping activities due to asthma (p=0.00). In addition, Polivka et al. (2011) found significant reductions in days with asthma symptoms (p=0.0), symptoms at nights due to asthma (p=0.00), and days with activity limited by asthma (p=0.00). Sweet et al. (2014) found significant reductions in days with asthma symptoms (p<0.01), nighttime awakening (p<0.01), and activity limitations (p<0.01).

For health care usage, the evidence was more varied (Appendix C). All studies found significant reductions in all measures of ED visits and unscheduled visits to the doctor, and only two found a significant decrease in measures of hospitalization. Largo et al. (2011) found significant reductions in the percentage of children who sought care at EDs (p=0.00), unscheduled visits to doctor (p=0.00), and hospitalizations (p=0.00).

Similarly, Turcotte et al. (2014) also found significant reductions in the number of ED visits (95% CI: 0.1, 0.2), doctor visits (95% CI: 0.2, 0.6), and hospitalizations (95% CI: 0.01, 0.8). Although Polivka et al. (2011) found significant reductions in the number of ED visits (p=0.00) and extra asthma-related doctor visits (p=0.00), there were no significant reductions in the mean number of hospitalizations. Similarly, Sweet et al. (2014) highlighted significant reductions in the number of ED visits (p<0.01), but not in hospitalization.

Single-trigger Interventions

This review found nine single-trigger interventions that assessed asthma morbidity post intervention. Most interventions were multicomponent (60%), whereas others were single-component (40%). Out of the nine interventions, two offered home visits (22%), five conducted in-home environmental assessment (55%), three conducted clinical asthma management education (33%), four delivered home environmental trigger-reduction (44%), and eight offered minor, moderate, and/or major home remediation (88%). Since each intervention addressed different triggers within the home, the type of intervention varied considerably. Two interventions provided efficient heating systems (22%), two removed mold and moisture (22%), two aimed to remove pests (22%), two installed air filtering equipment (22%), and one focused on house dust mite avoidance (11%). Due to differences in the remediation and education offered, results are presented based on remediation type and whether or not education was provided and analyzed per outcome type.

No remediation and only education

One study, rated weak, evaluated a single-trigger intervention that provided no remediation and only education. This RCT provided monthly counselling for house dust mite removal by educating asthmatic children's caretakers on washing bedding, cleaning the living room floor with a powerful vacuum, and removing stuffed toys, furry pets, and carpets (Nishioka et al., 2006). This study found that the frequency of asthma attacks reduced significantly (p=0.00)(Table 4).

Moderate remediation and no education

Two single-trigger intervention studies evaluated moderate remediation and no education, which included installation of air filtering equipment (Lajoie et al., 2014; Lanphear et al., 2011). Both of these studies were RCTs that measured asthma symptoms and health care usage.

Two RCTs, one rated strong and another rated moderate, which assessed the impact of air cleaning equipment, found varied evidence showing significant reductions in only one out of six measures of asthma symptoms (Table 5). One trial, which installed Energy Recovery Ventilators (that transfer moisture through a semi-permeable heat transfer core into the incoming outdoor air stream) showed significant improvements in wheezing (95% CI: -41.8, -2.3), but not in daytime/nighttime coughing, breathlessness, and disturbed sleep (Lajoie et al., 2014). The second trial installed two high-efficiency particulate air filters (HEPA) with activated carbon in the child's bedroom and main activity room. This trial did not show any significant improvements in shortness of breath, wheeze, tightness in chest, or difficulty sleeping (Lanphear et al., 2011).

One RCT that evaluated Energy Recovery Ventilators found no significant reductions in uncontrolled asthma (Lajoie et al., 2014).

Findings on health care usage were also varied (Table 5). One trial that assessed the impact of HEPA filters found significant reductions in unscheduled asthma-related visits to health care providers ($p<0.05$) (Lanphear et al., 2011). However, the second trial, which assessed Energy Recovery Ventilators, did not find any significant reductions in ED visits and hospitalizations (Lajoie et al., 2014).

Minor and moderate remediation with education

Two single-trigger intervention studies evaluated minor and moderate remediation aimed at pest removal (Levy et al., 2006; Pongracic et al., 2008). One study was a prospective cohort (Levy et al., 2006) and one was an RCT (Pongracic et al., 2008). Both studies measured improvements in asthma symptoms and health care usage.

Findings on asthma symptoms varied (Table 6). One RCT, rated moderate in quality, assessed the impact of an intervention aimed at eliminating pests, education about kitchen cleaning and food storage, filling rodent access points, and providing vacuum cleaners. This study did not find significant reductions in any of the four asthma symptom measures, which included symptom days, days with wheeze, nights with lost sleep, and days of reduced activity (Pongracic et al., 2008). Results from one cohort study, rated moderate, provided clinical education, integrated pest management, one-time intensive cleaning, and replacement of mattresses with microfiber technology mattresses. In this cohort, significant reductions were found in respiratory score ($p=0.00$), but not in asthma attacks (Levy et al., 2006).

For health care usage, results found no significant effect (Table 6). One RCT and one cohort study found no significant reductions in any measures of hospitalizations, unscheduled doctor visits, and physician phone consultations for asthma care (Levy et al., 2006; Pongracic et al., 2008).

Major remediation with or without education

Four single-trigger intervention studies evaluated major remediation (Johnson et al., 2009; Howden-Chapman et al., 2008; Kercsmer et al., 2006; Somerville et al., 2000). Out of the four studies, two were RCTs and two were prospective cohorts. Two studies installed efficient heating systems (Howden-Chapman et al., 2008; Somerville et al., 2000), and two aimed to remediate mold and moisture (Johnson et al., 2009; Kercsmer et al., 2006). All four studies measured asthma symptoms and two measured health care usage (Howden-Chapman et al., 2008; Kercsmer et al., 2006).

Two studies, both rated strong, evaluated the impact of heating systems and found significant reductions in most measures of asthma symptoms, but not health care usage (Howden-Chapman et al., 2008; Somerville et al., 2000) (Table 7). Results from one RCT that assessed the impact of installing a gas central heating system showed significant reductions in all three measures of asthma symptoms, which included daytime/nighttime coughing ($p=0.00$), daytime/nighttime wheezing ($p=0.00$), and breathlessness ($p=0.00$) (Somerville et al., 2000). Results from one cohort study that evaluated efficient heating systems (heat pump, wood pellet burner, or flued gas) found reductions in morning coughing ($p=0.00$), daytime coughing ($p=0.06$), morning wheezing ($p<0.01$), nighttime coughing ($p=0.01$), and nighttime wheezing ($p<0.01$), but not in daytime wheezing (Howden-Chapman et al., 2008). This cohort study also measured health care usage and found significant reductions in visits to doctors ($p=0.01$) (Howden-Chapman et al., 2008).

Results for mold remediation interventions were more varied than heating interventions (Johnson et al., 2009; Kercsmer et al., 2006) (Table 8). One RCT, rated strong, measured remediation of water infiltration, water-damaged building materials, and alterations to heating, ventilation, and air conditioning. This study did not find significant reductions in symptom days or ED visits (Kercsmer et al., 2006). Findings from the cohort study, rated moderate, evaluated mold remediation, repair of water intrusion sources, and installation of one or combination of heating, ventilating, and air conditioning (HVAC) servicing, pleated Allergy Zone furnace filter dehumidifier, and/or room air cleaners. This study showed significant reductions in daytime coughing from HVAC and dehumidifier only ($p<0.05$) and in breathing problems from all interventions provided ($p<0.05$)(Johnson et al., 2009). However, they did not find any significant reductions in wheezing, shortness of breath, and asthma attack (Johnson et al., 2009).

Discussion

A brief summary of main findings

This review found that multi-trigger interventions that offered multiple components were effective at reducing asthma symptoms and health care usage among low-income asthmatic children. Results from the evaluations of multi-trigger interventions showed that asthma symptoms and control exhibited greater rates of reduction when compared to health care usage reduction. Within the category of single-trigger interventions, one study on house dust mite avoidance found significant reductions in asthma symptoms. Studies that evaluated major heating efficiency remediation found significant reductions in most asthma symptoms measured, but reductions in health care usage were varied. However, interventions that provided moderate remediation, and those that conducted major mold remediation, found inconclusive evidence on reductions in asthma symptoms and health care usage among low-income children.

Interpretation of findings and alignment with other studies

This review found that multi-trigger, multicomponent interventions are effective. This finding is supported by other reviews that found that multi-trigger, multicomponent interventions are more effective than single-trigger and single-component interventions (Croker et al., 2011; Krieger, 2010). Childhood asthma is a complex problem, which arises from a dynamic interplay of factors. Such problems do not respond to simple, independent, one-off solutions. Instead, they require efforts at different levels (Riley et al., 2015). Although multifaceted solutions are generally more costly than simple ones, a review found that these interventions are still relatively cost-effective and can match or even exceed their program costs (Nurmagambetov et al., 2011). I argue that multi-trigger, multicomponent interventions provide an effective and low-cost solution to a complex condition like childhood asthma morbidity.

Furthermore, the current review found that asthma symptom outcomes were more commonly improved compared to health care usage outcomes. However, this may be due to short follow-up times of included studies. Reduction in health care usage is often followed by reductions in asthma symptoms (Bahadori et al., 2009). It is possible that health care usage may have reduced after the last follow-up visit, which the intervention was unable to measure. As such, the potential impact of multi-trigger interventions on reductions in health care usage should not be disregarded.

In addition to confirming our findings, other reviews demonstrate a broader impact of multi-trigger, multicomponent interventions. Crocker et al. (2010) and Krieger (2010) found that these interventions not only lead to reductions in clinical asthma outcomes, but also indoor air quality, productivity, and quality of life (Crocker et al., 2010; Krieger, 2010). I also found that these interventions are effective in workplaces and schools, as well as on adults with asthma (Crocker et al., 2010; Krieger, 2010). With a more fulsome picture of the impact of multi-trigger interventions, Iargue that these interventions could be offered in a variety of settings and to diverse populations.

Strengths and limitations of this review

This review provides robust evidence on the effectiveness of indoor air quality interventions for the following reasons:

- Randomized controlled trials and prospective cohort studies present high quality evidence
- The review conducted a comprehensive search in eight databases
- The review mainly included strong and moderate quality evidence and findings are aligned with supporting literatures

However, there are some limitations regarding the overall completeness and applicability of evidence presented. For example, since meta-analysis was not conducted, I was not able to make conclusions on the size of effect, which may limit our ability to apply these findings in a confident manner. Moreover, each intervention category presented a limited number of studies, some of which had relatively small sample sizes, further reducing the confidence of results. I was also unable to assess sustainability of included interventions because studies had limited follow-up times. Because the participants of included studies were mainly low-income, urban minority children, findings may only be applicable to this population. Potential biases that may impact the results of this review include: selection bias, publication bias, reporting bias, and confounding factors (refer to Appendix G for a more detailed description of these biases).

Implications for research

Future research should aim to improve the evidence base for the research question asked in this review. When doing so, studies evaluating indoor air quality interventions should aim to use standardized and validated tools to measure asthma morbidity. This approach will allow researchers to better compare the impact of these interventions (i.e. consistent outcomes), increasing the ability to draw more confident results. Furthermore, in order to avoid collecting incorrect outcome data from participants (who may overestimate improvements in their health after receiving the intervention), future studies should focus on confirming diagnosis and symptom progression by physicians, rather than relying solely on self-reported data.

In order to build on the evidence presented in this review, there are some questions that still need to be answered. For instance, there is a need to understand the independent contributions of intervention components in relation to overall intervention effectiveness. It would also be useful to understand the required intensity needed for conducting an indoor air quality intervention effectively, how these interventions could be integrated in the health care system or housing sector, and what organizations would be the most effective implementers.

Implications for policy and practice

With the evidence presented in this review, there are several activities that the health care, housing, and public health sector could lead to improve housing quality for low-income asthmatic children in Toronto. The health care sector is the first point of contact for identifying and targeting asthmatic children. Health care providers could educate caregivers of asthmatic children on the importance of reducing multiple allergens in homes. In addition, through chest clinics and home care Public Health Nurses could conduct inspections and remediation of multiple triggers in the homes of asthmatic children.

The City of Toronto could build on existing initiatives to improve housing quality for asthmatic children living in poor conditions. Multi-trigger interventions identified in this review were implemented in a range of neighbourhoods across the United States. These interventions have shown to effectively improve asthma outcomes and Toronto Public Health could develop a similar intervention for low-income neighbourhoods. Alternatively, an environmental component could be incorporated in family health programs offered by Toronto Public Health, such as the Healthy Babies Healthy Children program, which conducts home visits through Public Health Nurses. This environmental component could focus on education and remediation of multiple household triggers that exacerbate asthma for low-income families living in poor quality homes. Outside of the public health sector, the Tower Renewal Program could lead initiatives to improve the air quality in some of Toronto's concrete towers in low-income neighbourhoods. Finally, the Multi-Residential Apartment Building Program could also be scaled up to target improvements in housing quality for low-income families.

At the provincial level, the Ministry of Health and Long Term Care oversees the Public Health School Asthma Program to create asthma friendly school environments. Since the household environment is an important determinant of health, and children spend a great amount of time in their homes, this program could be expanded in residential settings for low-income families with asthmatic children. In its delivery, the program could remediate multiple triggers, while offering several components such as education, home visits, and household remediation. Through these initiatives, the health care, public health, and housing sectors could further their efforts to improve living conditions for vulnerable children.

Conclusion

Asthma is a common chronic condition among children. Low-income children are more likely to live in homes with poor indoor air quality, increasing their risk of exposure to indoor air allergens. This poses a health equity concern. This systematic review provides evidence on how to improve indoor air quality for asthmatic children living in low-income households. The available literature identifies that the most effective way to mitigate a complex illness like asthma is through multi-trigger, multicomponent interventions. Improving indoor air quality through effective, multifaceted approaches could reduce disparities in childhood asthma morbidity. The health care, public health, and housing sectors could lead initiatives that improve housing quality for low-income asthmatic children living in Toronto's substandard homes.

Appendix A: PICO criteria

Criteria	Description of Criteria
Population	This review included children between 0-18 years with an existing asthma diagnosis. Low-income children with asthma living in urban and suburban environments are more vulnerable to indoor air allergens compared to wealthy children, children at risk of asthma, children living in rural areas, and adults with asthma (MOHLTC, 2013; Kitch et al., 2000). As such, they are at the highest risk of using health care resources and more likely to experience adverse consequences associated with asthma (Kitch et al., 2000).
Intervention	Interventions in this review aimed to reduce one or more housing-related environmental triggers that exacerbate asthma. These include mold, cockroach, rodents, house dust mites, pet dander, and smoke (Lin et al., 2012; Belanger et al., 2003; Rauh et al. 2002). Indoor contaminants (i.e. lead, particulate matter) are not associated with asthma (Breysse, Diette, Matsui, Butz, Hansel, and McCormack, 2010). Thus, interventions that address indoor contaminants were excluded.
Comparison	Comparison groups received one of the following: no intervention; general asthma education, or routine medical care. Comparison groups that received other environmental intervention were excluded because the aim of this review is to understand the impact of indoor air quality interventions against no environmental intervention (which could otherwise underestimate the effect of the intervention being measured).
Outcome	Only clinical asthma morbidity outcomes were included in this review. These outcomes included: 1) asthma symptoms (coughing, wheezing, shortness of breath, tightness in chest, sleep limitations, activity restrictions, and asthma attacks), 2) uncontrolled asthma, and 3) asthma-related health care usage (emergency department [ED] visits, hospitalization, and clinic visits). Asthma morbidity is composed of asthma symptoms, asthma control, health care usage, productivity, and quality of life. However, clinical outcomes show the direct consequences of asthma exacerbation, where as quality of life and productivity indicators may be influenced by external factors. As such, in order to maintain a feasible scope, only proximal outcomes were included.

Appendix B: Database-specific search strategies

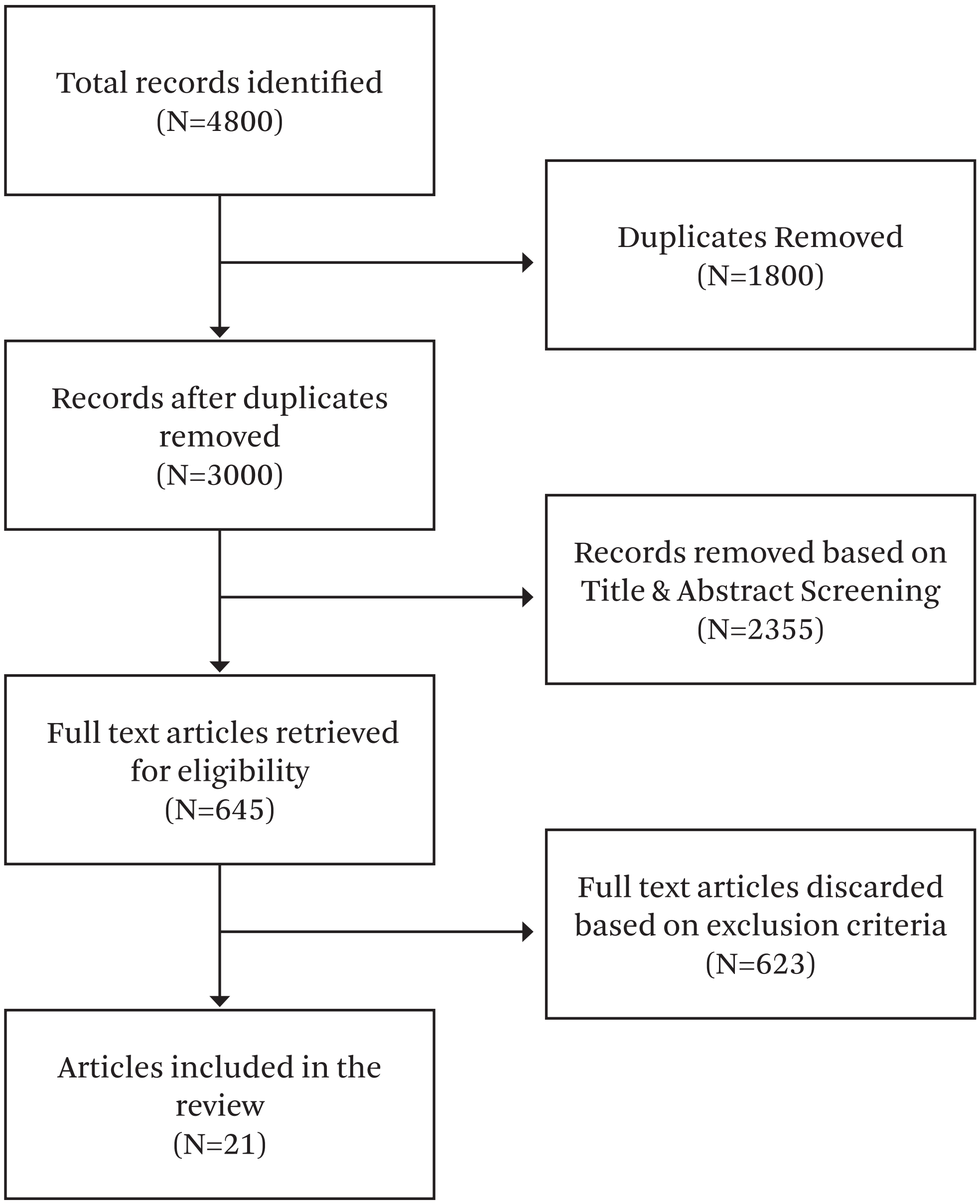
Database	Search strategy
BIOSIS	(asthma* OR cough* OR wheez*) AND (“indoor air quality” OR “indoor air pollution” OR allergen* OR “home environment” OR “indoor environment”) AND (child* OR infant*)
CINAHL	(asthma* OR cough* OR wheez* OR breath*)) AND (“indoor air quality” OR “indoor air pollution” OR “indoor allergen” OR “hous* allergen” OR “home allergen” OR “home environment” OR “hous* environment” OR “indoor environment” OR “indoor trigger” OR “hous* trigger” OR “home trigger”)
Cochrane	(asthma* OR cough* OR wheez*) AND (“indoor air quality” OR “indoor air pollution” OR allergen* OR “home environment” OR “indoor environment”) AND (child* OR infant*)
EMBASE	(asthma* OR cough* OR wheez*) AND (“indoor air quality” OR “indoor air pollution” OR allergen* OR “home environment” OR “indoor environment”) AND (child* OR infant*)
Medline	(asthma*.mp. or exp Asthma/ or exp Cough/ or cough*.mp. or wheez*.mp. or breath adj2 shortness or tightness adj2 chest) AND (indoor air quality.mp. or exp Air Pollution, Indoor/ or triggers adj3 home or home adj3 environment or allergen*.mp. or Allergens/) limit 22 to (english language and humans and yr=”2000 -Current” and (“all infant (birth to 23 months)” or “all child (0 to 18 years)” or “newborn infant (birth to 1 month)” or “infant (1 to 23 months)” or “preschool child (2 to 5 years)” or “child (6 to 12 years)”)
PAIS	(asthma* OR cough* OR wheez* OR breath*) AND (“indoor air quality” OR “indoor air pollution” OR “indoor allergen” OR “home allergen” OR “hous* allergen” OR “indoor environment” OR “home environment” OR “indoor trigger” OR “hous* trigger” OR “home trigger”)
PubMed	(asthma* OR cough* OR wheez* OR breath*)) AND (“indoor air quality” OR “indoor air pollution” OR “indoor allergen” OR “hous* allergen” OR “home allergen” OR “home environment” OR “hous* environment” OR “indoor environment” OR “indoor trigger” OR “hous* trigger” OR “home trigger”)
SCOPUS	asthma* OR cough* OR wheez* OR “breath W/3 short*” OR “chest W/3 tight*”) AND TITLE-ABS-KEY (“indoor air quality” OR “indoor air pollution” OR “indoor W/3 allergen” OR “home W/3 allergen” OR “hous* W/3 allergen” OR “indoor W/3 environment” OR “home W/3 environment” OR “indoor W/3 trigger” OR “hous* W/3 trigger” OR “home W/3 trigger”) AND TITLE-ABS-KEY (child* OR infant)

Appendix D: Quality assessment table

1=strong, 2=moderate, 3=weak

Study	Selection Bias	Study Design	Confounders	Blinding	Data Collection Method	Withdrawals and Dropouts	Overall score
Bryant-Stephens et al., 2008	2	1	3	2	1	2	Moderate
Carrillo et al., 2015	2	2	2	3	1	1	Strong
Eggleston et al., 2005	2	1	2	1	1	1	Strong
Largo et al., 2011	3	2	2	2	2	1	Moderate
Morgan et al., 2004	2	1	2	3	2	1	Moderate
Polivka et al., 2011	2	2	2	3	2	2	Strong
Primomo et al., 2006	3	2	2	2	1	2	Moderate
Shani et al., 2015	3	2	2	2	2	1	Moderate
Sweet et al., 2014	2	2	2	2	1	3	Moderate
Turcotte et al., 2014	2	2	2	2	1	2	Strong
Turyk et al., 2013	2	2	2	2	2	2	Strong
Williams, 2006	3	1	2	2	3	3	Weak
Johnson, 2009	3	2	2	2	1	1	Moderate
Howden-Chapman, 2008	2	1	3	2	2	1	Strong
Kercsmer, 2006	2	1	3	2	2	1	Strong
Somerville, 2000	2	2	2	3	2	2	Strong
Levy et al., 2006	2	2	2	2	3	2	Moderate
Pongracic et al., 2008	1	1	2	3	2	1	Moderate
Lajoie, 2014	2	1	2	3	2	2	Strong
Lanphear, 2011	1	2	2	3	1	2	Moderate
Nishioka et al., 2006	2	2	2	2	3	3	Weak

Appendix E: Flow chart of study inclusion and exclusion



Appendix F: Definitions of study designs used and hierarchy of evidence

Randomized Controlled Trial: A type of scientific experiment, which randomly (by chance alone) assigns people into an experimental or control group. The experimental group receives a treatment and the control group receives no intervention. A well-designed randomized controlled trial is generally the strongest study design for evaluating an intervention's effectiveness (Figure 1).

Pre-to-post Cohort Study: A pre-post study examines whether participants in an intervention improve or become worse off during the course of the intervention, and then attributes any such improvement or deterioration to the intervention. Although this type of study design is just below the randomized controlled trial in the hierarchy of evidence (Figure 1), a problem is that without reference to a comparison group, it cannot confidently answer whether participants' improvement or deterioration would have happened without the intervention.

Figure 1. Hierarchy of evidence for public health intervention research

Appendix G: Potential biases in this review

Biases	Description
Publication bias	• No grey literature was searched • Non-English language publications were excluded • Only one author reviewed titles, abstract, and full text and extracted data
Reporting bias	• Possibility for errors in exposure assessment as participants may have been exposed to allergens in other locations that were not considered in this review • Lack of blinding could overestimate the change in outcomes • Studies collected asthma symptom data through self-reports, which could also overestimate the change in outcomes • Outcomes were not measured consistently across studies
Confounding	• Prospective cohort studies that did not include a comparison group make it impossible to know what could have happened without the intervention. Asthma severity differs based on seasonality, amount of time spent in certain indoor environments, and amount of air pollution. The results may be impacted by these confounders.
Selection bias	• Participants in studies included in this review were referred through clinics. Inclusion of participants may have depended on their relationships with physicians or how willing they are to make change. In essence, these participants may not be representative of the target population.

Appendix C: Summary of Findings Table

Table Legend: (▼) = significant decrease from baseline (compared to control group only for RCTs); (▲) = significant increase from baseline (compared to control group only for RCTs); (ND) = no significant change from baseline (compared to control group only for RCTs)

Multi-trigger, Multicomponent Interventions					
Reference	**Study Design**	**Participant Characteristics**	**Intervention**	**Comparison**	**Results**
Bryant-Stephens et al. (2008).	RCT (N=128/115) Follow-up: 12 months	1-18 years; low income; mainly African American	**6 Home visits by trained by trained Home Visitors over 6 months** In-home environmental assessment; asthma management education; environmental trigger-reduction education; minor and moderate remediation: pest baits, cleaning supplies, and vacuum cleaners; effective bedding materials	Control: Delayed intervention	Health Care Usage (▼) Mean number of **inpatient length of stay** from 0.66 to 0.35 ($p<0.05$) (▼) Mean number of **ED visits** from 1.99 to 1.02 ($p<0.01$) (▼) Mean number of **asthma-related regular sick visits** from 1.32 to 0.84 ($p<0.05$)
Eggleston et al. (2005).	RCT (N=50/50) Follow-up: 6 months and 12 months	6-12 years; low income; ethnicity not specified	**3 Home Visits by trained Environmental Educators over 5 months** In-home environmental assessment; asthma management education; environmental trigger-reduction education; minor and moderate: provision of integrated pest management for cockroach and rodent extermination, allergen proof bedding, bait traps, and HEPA	Control: Delayed intervention	Asthma Symptoms (▼)Children reporting **daytime asthma symptoms** at 6 months from 58% to 50% ($p=0.01$), and at 12 months to 55% ($p<0.05$). (▼) Children reporting **symptoms with exercise** at 6 months from52% to 33% ($p<0.01$) but not at 12 months. (▼) Children reporting **nighttime symptoms** at 6 months from 42% to 36% ($p<0.05$), but not at 12 months. (▼) Children reporting **asthma interference with activity** from 71% to 40% ($p<0.05$), but not at 12 months.

Morgan et al. (2004).	RCT (N=469/468) Follow-up: 1 and 2 years	5-11 years; low-income; mainly Black and Hispanic groups	**7 Home Visits by Environmental Counsellors over 6 months** In-home environmental assessment; asthma management education; environmental trigger-reduction education; minor and moderate remediation: provision of allergen-impermeable bedding cover, vacuum cleaner with HEPA air filters, HEPA air purifiers, and professional pest control	Control: Delayed intervention	**Year 1** **Asthma symptoms** (▾) Mean number of **days with wheeze** (2.65±0.11 vs. 3.43±0.11; p=0.00) (▾) Mean number of **days that child had to slow down or stop play** because of asthma (2.34±0.10 vs. 2.84±0.10; p=0.00) (▾) Mean number of **nights where child woke up** due to asthma (1.55±0.08 vs. 2.17±0.08; p=0.00) **Health care usage** (▾) Mean number of **Unscheduled visits to ED or clinic** for asthma (2.22±0.12 vs. 2.57±0.13; P<0.05) (ND) Percentage of **hospitalizations** for asthma **Year 2** **Asthma symptoms** (▾) Mean **number of days with wheeze** (2.28±0.11 vs. 2.87±0.11; p=0.00) (▾) Mean **number of days that child had to stop or slow activity due to asthma** (1.67±0.10 vs. 2.13±0.10; p=0.00) (▾) Mean **number of nights that child woke up because of asthma** (1.27±0.08 vs. 1.57±0.08; p=0.01) **Health care usage** (ND) Mean **number of unscheduled asthma-related visits to ED or clinics** (ND) Percentage of **hospitalizations** for asthma

Williams et al. (2006).	RCT (N=84/77) Follow-up: 12 months	5-12 years; low income; all Non-Hispanic, Black	**3 Home Visits by Community Health Workers** In-home environmental assessment; asthma management education; environmental trigger-reduction education regarding smoking, and food handling practices, proper washing and drying of bedding and carpets, mold and humidity; minor remediation: provided cockroach eradication through gel and professional home cleaning; and placement of roach bait	Control: Delayed intervention	**Asthma Symptoms** (▼) functional severity score (p<0.01)
Polivka et al. (2011).	Prospective Cohort (N=84) Follow-up: 6 months	1-18 years; low income; ethnicity not specified	**Home Visits by Health Educator and Community Outreach Worker** In-home environmental assessment; asthma management education; environmental trigger-reduction education with an individuals tailored healthy home action plan; minor, moderate, and major remediation: allergen cleaning, mold remediation, repair leaky roofs and pipes, seal crack and crevices, pest control, roach control, and supplies like such as mattress, bedding materials, cleaning kits, and dehumidifier		**Asthma symptoms** (▼) Mean number of **symptom days** from 5.0 to 2.2 (p=0.00) (▼) Mean number of **symptom nights** from 3.6 to 1.8 (p=0.00) (▼) Mean number of **days with activity limited by asthma** from 4.1 to 1.7 (p=0.00) **Health care usage** (▼) Mean number of **ED visits** from 1.7 to 0.4 (p=0.00) (▼) Mean number of **extra asthma-related doctor visits** from 1.9 to 0.5 (p=0.00)
Primomo et al. (2006).	Prospective Cohort (N=60) Follow-up: 12 months	1-18 years; low income; 68% Caucasians, 19% African Americans, and 16% other	**Home Visits by Community Outreach Worker** In-home environmental assessment; asthma management education; environmental trigger-reduction education; minor remediation: allergen proof bedding, and door mats		**Health care usage** (▼) Percentage of children **hospitalized** from 30% to 18% (p<0.01) (ND) Percentage of children who had **emergency room visits** (ND) Percentage of children who had **unscheduled doctor visits**

Shani et al. (2015).	Prospective Cohort (N=132) Follow-up: 12 months	2-17 years; low income; ethnicity not specified	**4 Home Visits by Peer Educators over 6 weeks** In-home environmental assessment; asthma management education; environmental trigger-reduction education; minor and moderate: received home kits with allergen-proof mattress. pillow encasings, cleaning supplies, storage bins, bait traps, and integrated pest management		**Asthma Control** (▼) **Child asthma control test** showed slightly significant improvements in asthma control (p=0.07) - The improvement was greater for children whose asthma was initially considered "severe" (p<0.01) **Health care usage** (▼) Mean number of **trips to the ER** (p<0.05) (ND) Mean number of **overnight hospital stay** (ND) Mean number of **visits to doctor**
Sweet et al. (2014).	Prospective Cohort (N=115) Follow-up: 6 months	0-18 years; low income; 71% African American; 16% White; 4% Hispanics, and 5% others	**Home Visits by Public Health Nurse or health educators** In-home environmental assessment; asthma management education; environmental trigger-reduction education; minor, moderate and major: bedding supplies, vacuum, and cleaning kits; pest management, dehumidifier; remediating mold and moisture or safety hazards; cleaning/repairing gutters, re-grading soil foundations, installing vents.		**Asthma symptoms** (▼) Mean number of **days with asthma symptoms** by a mean of 2.4 days (5.01±4.27 to 2.66±3.86; p<0.01) (▼) Mean number of **days with nighttime awakenings** by a mean of 1.9 night (3.18±3.91 to 1.31±2.72; p<0.01) (▼) Mean number of **days with activity limitations** by a mean of 2.2 days (3.84±4.61 to 1.62±3.53; p<0.01) **Health care usage** (▼) Mean number of **ED visits** by a mean of 0.67 visits (1.17±3.06 to 0.50±0.67; p<0.01) (ND) Mean number of **hospitalizations**
Turcotte et al. (2014).	Prospective Cohort (N=170) Follow-up: 12 months	Younger than 15 years; low income; 53% Hispanic, 15% Asian, 14% other, 12% white, 8% black	**4 to 9 Home Visits by Environmental Assessors** In-home environmental assessment; asthma management education; environmental trigger-reduction education; minor, moderate, and major: vacuum cleaners, HEPA filters, implemented integrated pest management, and some structural interventions as needed		**Asthma symptoms** (▼) Mean number of **episodes of wheezing** from 6.40 to 2.30 (95% CI: 2.7, 5.6) (▼)Mean number of **asthma attacks** from 0.80 to 0.20 (95% CI: 0.2, 1.0) (▼)Mean number of children reporting **difficulty sleeping all the time** (95% CI: 4.2, 15.0) **Health care usage** (▼)Mean number of **ED visits** from 0.20 to 0.04 (95% CI: 0.1, 0.2) (▼)Mean number of **doctor visits** from 0.70 to 0.20 (95% CI: 0.2, 0.6) (▼)Mean number of **hospitalizations** from 0.05 to 0.00 (95% CI: 0.01, 0.8)

Turyk et al. (2013).	Prospective Cohort (N=218) Follow-up: 12 months	0-18 years; low-income; ethnicity not specified	**7 Home Visits by Community Health Educators** In-home environmental assessment; asthma management education; environmental trigger-reduction education; minor and moderate remediation: individually tailored modifications such as providing allergen proof bedding, integrated pest management		**Asthma Control** (▼) Percentage of children reporting **uncontrolled asthma** from 62% to 30% ($p<0.01$) **Health Care Usage** (▼)Percentage of children reporting **hospitalizations** from 15.6% to 4.6% ($p=0.00$) (▼)Percentage of children reporting **ED visits** from 46.8% to 23.9% ($p=0.00$) (▼)Percentage of children reporting **urgent care** from 46% to 19.4% ($p=0.00$)
Carrillo et al. (2015).	Prospective Cohort (N=89) Follow-up: 12 months	1-17 years; low-income; mainly Hispanic	**3 Home Visits by trained Promotoras over 9 months** In-home environmental assessment; asthma management education; environmental trigger-reduction education; minor remediation: allergen-proof mattress and pillow encasings		**Asthma Symptoms** (▼) Percentage of children with **asthma attacks** or **trouble breathing** from 39.2% to 9.2% ($p=0.00$) (▼) Percentage of children with **symptoms of wheezing or whistling** when breathing out from 57.1% to 34.5% ($p=0.00$) (▼) Percentage of children having **difficulty sleeping** due to asthma from 60% to 33.8% ($p=0.00$) (ND) Percentage of participants reporting **ED visits** did not change (ND) Percentage of participants reporting **overnight hospital stays** dropped from 6% to 1% pre to post intervention, but this was not significant (▼) Percentage of participants with **one of more clinic visits** from 51% to 31% ($p<0.05$)

Largo et al. (2011).	Prospective Cohort (N=243) Follow-up: 6 months	Less than 18 years; low income; 38% African American, 27% White, 25% multiracial, 10% Hispanics	**4 Home Visits by Program Staff over 6 months** In-home environmental assessment; asthma management education; environmental trigger-reduction education; minor, moderate, and major remediation: installation of basic products (furnace filters, HEPA vacuum, pest control, cleaning supplies, bedding covers, smoking cessation kits, foam crack sealant) and custom products (vent installation, carpet removal, minor repairs, landscaping for water drainage, pest extermination, etc.)		**Asthma Symptoms** (▼) Mean number of day with **wheezing in the morning** from 6.2 to 3.1 (p=0.00) (▼) Mean number of children who woke up due to **wheezing, tightness in chest, or a cough** from 8.7 to 3.3 (p=0.00) (▼) Mean number of days with **shortness of breath** from 9.4 to 3.4 (p=0.00) (▼) Mean number of days with **wheezing, tightness in chest or cough** from 12.0 to 4.9 (p=0.00) (▼) Mean number of days of **slowing down to stopping activities due to asthma** from 9.1 to 3.3 (p=0.00) **Health care usage** (▼) Percentage of children that sought **unscheduled visits to health care** by 48% (p<0.00) (▼) Percentage of children that sought care at **ED** by 53%(p=0.00) (▼) Percentage of children that had **hospital visits** by 68% (p=0.00)

Single Trigger Interventions					
Reference	**Study Design**	**Participant Characteristics**	**Intervention**	**Comparison**	**Results**
Howden-Chapman et al. (2008).	RCT (N=175/174) Follow up: 6 months	6-12 years; low income; 72% Maori; 20% Pacific people; 8% others	**Heating system remediation** In-home environmental assessment; no education provided; major remediation: Installation of efficient heating units (heat pump, wood pellet, burner, or flued gas) replacement in homes	Control: Delayed intervention	**Asthma Symptoms** (▼) Frequency of **nighttime coughing** (mean ratio: 0.72; 95%CI 0.59 to 0.89; p=0.01) (▼) Frequency of **nighttime wheezing** (mean ratio: 0.67;95% CI: 0.49 to 0.93; p<0.01) (▼) Frequency of **morning coughing** (mean ratio: 0.67; 95% CI: 0.53 to 0.84; p<0.00) (▼) Frequency of **morning wheezing** (mean ratio: 0.60; 95% CI: 0.45 to 0.81; p<0.01) (▼) Frequency of **daytime coughing** had marginal significance (mean ratio: 0.84; 0.70 to 1.01; p=0.06) (ND) Frequency of **daytime wheezing** **Health care usage** (▼) Mean number of **visits to doctor** for asthma (mean ratio: 0.40; 95% CI: 0.11 to 0.62; p=0.01)
Kercsmer et al. (2006).	RCT (N=29/33) Follow-up: 12 months	2-17 years; low-income; all African American	**Home Visits by trained sanitarians aimed at moisture/mold control** In-home assessment; asthma management education; major remediation: reducing water infiltration, removing water-damaged building materials, and alterations to heating, ventilation, and air conditioning, lead hazard control, and environmental cleaning	Control: received educational resources on asthma management	**Asthma symptoms** (ND) Mean number of days with **symptoms** **Health care usage** (ND) Percentage of children reporting **one or more ED visits**

Pongracic et al. (2008).	RCT (N=150/155) Follow-up: 2 years	5-11 years; low income; 50% African American, 30% Hispanic, 20% other	**Rodent Extermination Remediation** Environmental trigger-reduction education about kitchen cleaning and proper food storage; minor and moderate remediation: Install HEPA vacuum cleaner and HEPA air filter in child's bedroom; fill rodent access points and traps throughout home	Control: Delayed intervention	Asthma symptoms (ND) Mean number of **maximum symptom days** (ND) Mean number of **days of wheeze** (ND) Mean number of **nights child lost sleep** (ND) Mean number of **days child's activity reduced** Health care usage (ND) Mean number of **hospitalizations** (ND) Mean number of **unscheduled asthma visits**
Lajoie et al. (2014).	RCT (N=43/40) Follow-up: 2 years	3-12 years; low income; ethnicity not specified	**Installation of Air Filtering Ventilation Equipment** No education; moderate remediation: Installation or modifications of either Energy Recovery Ventilators or Heat Recovery Ventilators. ERVs and HRVs transfer moisture through their semi-permeable heat transfer core into the incoming outdoor air stream	Control: Delayed intervention	Asthma symptoms (ND) Percentage of children with **at least one symptom** (ND) Percentage of children **coughing** (ND) Percentage of children reporting **breathlessness** (ND) Percentage of children reporting **disturbed sleep** (▼)Percentage of children reporting **wheezing** (95% CI: -41.8, -2.3) (▼)Percentage of children reporting **4 or more wheezing episodes** (95% CI: -38.8, -1.1) (ND) Percentage of children **coughing at night** Asthma control (ND) Mean number of months with **asthma control** over 4 months Health care usage (ND) Percentage of children reporting **emergency care at ED** (ND) Percentage of children reporting **emergency care at hospitalizations**

Lanphear. (2011).	RCT (N=105/111) Follow-up: 12 months	6-12 years; low income;	**Installation of Air Filtering Equipment** No education; moderate remediation: Two HEPA air cleaners with activated carbon in child's bedroom and main activity room	Control: Delayed intervention	**Asthma symptoms** (ND) **Shortness of breath** (ND) **Tightness of chest** (ND) **Wheeze** (ND) **Difficulty sleeping** **Health care usage** (▼) **Unscheduled asthma-related visits** to health care providers by 18.5% ($p<0.05$)
Nishioka et al. (2006).	RCT (N=24/12) Follow-up: 12 months	7 years or younger; low income; ethnicity	**Monthly counselling for HDM avoidance (>60 minutes)** Environmental trigger-reduction education on washing bedding, and cleaning living room floor with a powerful vacuum floor; removal of stuffed toys, furry pets, and carpets	Control: Asthma management education	**Asthma symptoms** (▼) Frequency of **asthma attacks** ($p=0.00$)
Somerville et al. (2000).	Prospective Cohort (N=104) Follow-up: 3 months	1-16 years: low income; ethnicity not specified	Heating system remediation Major remediation: Installation of gas central heating to produce a warm, dry, and energy efficient house.		**Asthma symptoms** (▼) Frequency of **daytime coughing** ($p=0.00$) (▼) Frequency of **nighttime coughing** ($p=0.00$) (▼) Frequency of **daytime wheezing** ($p=0.00$) (▼) Frequency of **nighttime wheezing** ($p=0.00$) (▼) Frequency of **breathlessness with exercise** ($p=0.00$) (▼) Frequency of **breathlessness** ($p=0.00$)
Levy et al. (2006).	Prospective Cohort (N=50) Follow-up: 10 months	4-17 years; low income; allergic to pests; 70% Hispanics, 28% African Americans, 2% Caucasians	**Home Visits by Community Health Nurse aimed at pest management** In-home environmental assessment; asthma management education and action plans; no environmental trigger-reduction education; minor and moderate: integrated pest management, one-time intensive cleaning, replacement of mattresses with microfiber technology mattress		**Asthma symptoms** (▼) Mean **respiratory symptom score** from 2.6 to 1.5 ($p=0.00$) (ND) Percentage of children reporting **asthma attacks** **Health care usage** (ND) Percentage of children who had to **call a doctor for asthma care** (ND) Percentage of children reporting **hospitalizations**

Johnson et al. (2009).	Prospective Cohort (N=219) Follow-up: 6 months	2-17 years; low income; 56% black, 33% white, 11% other	**Moisture/mold control** In-home environmental assessment; asthma management education; environmental trigger-reduction education; moderate and major remediation: removal of visible mold; repair of water intrusion sources; AND one or combination of: HVAC servicing and installation of pleated Allergy Zone furnace filter basement dehumidifier, and room air cleaners		**Asthma Symptoms** (▾) Frequency of **coughing** with HVAC and dehumidifiers only ($p<0.05$) (ND) Frequency of **wheezing** with any interventions (ND) Frequency of **shortness of breath** with any interventions (▾) Percentage of children reporting **breathing problems** all interventions individual or combined ($p<0.05$) (ND) Percentage of children reporting **asthma attacks**

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