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A multi-city study of indoor air quality in green vs non-green low-income housing

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Abstract

Objectives—The condition of the home is a strong predictor of exposure to environmental contaminants; low-income households being particularly vulnerable. Therefore, improving housing standards is a priority. Housing built to “green” standards, with improved building methods and materials, has been suggested to reduce contaminants. However, evidence is limited as to which contaminants are reduced. The Green Housing Study was conducted to address this issue. The study hypothesis was that housing built using green components has lower concentrations of environmental contaminants compared to conventional housing.

Methods—A repeated-measures, 12-month cohort study was performed in three U.S. cities. Data were collected in the home at three time points. The level of contaminants were estimated using air samples for particulate matter and black carbon, dust samples for aeroallergens and pesticides, and resident or study staff reporting evidence of mold. To investigate source(s) of $PM_{2.5}$ and black carbon, multivariable models using stepwise variable selection were developed.

Results—In adjusted generalized estimating equations (GEE) models, black carbon concentration (mcg/m3) (β = −0.22, 95% CI = −0.38 to −0.06, p = 0.01), permethrin (OR = 0.28, 95% CI = 0.15–0.49, p <0.0001), and reported mold (OR = 0.29, 95% CI = 0.13–0.68, p = 0.003) were significantly lower in green homes. Cockroach antigen was also lower in green homes (OR = 0.59, 95% CI = 0.33–1.08, p = 0.09), although not statistically significant. We found

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that 68% of $PM_{2.5}$ was explained by dwelling type and smoking and 42% of black carbon was explained by venting while cooking and use of a gas stove.

Conclusions—This study provides quantitative data suggesting benefits of incorporating green building practices on the level of numerous environmental contaminants known to be associated with health. Occupant behavior, particularly smoking, is an important contributor to indoor air pollution.

Keywords

Indoor air quality; $PM_{2.5}$; black carbon; cockroach exposure; mold; green housing

1. Introduction

The influence of housing on health has been recognized for decades. Characteristics of the home are associated with the physical and mental health of occupants (Bonnefoy 2007, DÁllesandro 2020) The condition of the home (Wilson 2010), type of building materials (Naranjo 2020), and occupant behavior (Um 2022) are strong predictors of exposure to numerous environmental contaminants. Some of the strongest data quantify the association between the home environment and exposure to lead-based paint, allergens, mold, and indoor air pollutants (Vardoulakis 2020, Naranjo 2020, Wilson 2010). Studies of indoor air quality suggest greater contamination indoors, as much as 2–5 times that of outdoor air (Schmidt 2008). These elevated exposures have been shown to affect or pose a hazard to health.

Exposure to indoor allergens, particularly cockroach and mouse, are strong predictors of asthma morbidity (Rabito 2017, Torjusen 2012). Mold and dampness is associated with adverse effects on respiratory health and may be associated with adverse birth outcomes (Harville and Rabito 2018, Lu 2022, Mudarri 2007). Common indoor air contaminants have also been found to exceed health-based standards for chronic exposure in a significant fraction of U.S. homes (Logue 2011). These findings, coupled with the fact that in the United States the majority of time is spent indoors at home, makes the home environment an important route of exposure for human health. Households with lower incomes are particularly vulnerable to contaminant exposure, given higher prevalence of indoor smoking, greater use of unvented heating and cooking appliances, and a propensity to live in smaller apartments within multifamily residences (CDC 1997, Underhill 2018). Therefore, improving housing standards, particularly for persons of low-income status, has become a priority for many industrialized nations (Ferguson 2020, Ormandy 2009).

The relationship between characteristics of the home environment, exposure to contaminants, and poor health has been established; interventions to reduce exposure are now the focus of research. Behavior change interventions aim to reduce exposure through promoting activities that create a healthier environment (e.g., eliminate smoking indoors, properly vent when cooking, reduce use of pesticides). These interventions target the individual and place the onus on the resident. In contrast, housing policies are interventions that target entire neighborhoods and rely less on the activities of individual residents. Green building is one such intervention. While there is no standard definition for 'green' building, it is generally accepted to be an approach that both saves energy and resources and minimizes environmental exposures to occupants. Approaches such as improving indoor air quality, reducing use of chemical products, and improved energy efficiency, are prime components. (Steinemann 2017). Numerous studies have been conducted on the effect of green building design on indoor air quality and other contaminants. Findings suggest reductions in the level of environmental pollutants, but most of these studies lack quantitative measures of environmental endpoints, have a small sample size, or lack a suitable comparison group. Few employ a longitudinal, repeated measures design (Xiong 2015, Colton 2015, Garland 2013, Breysse 2015).

This study addresses those gaps using data from the Green Housing Study, a multi-site, prospective cohort study sponsored by the Center for Disease Control and Prevention (CDC), U.S. Department of Housing and Urban Development (HUD), and the U.S. Environmental Protection Agency (EPA). The primary aims of the study were 1) to quantify the concentration of select air pollutants, chemicals, and allergens in the home of children with asthma and to examine if concentrations vary between housing renovated to green standards and conventional housing and 2) to assess the effect of green housing on the health of children with asthma. This analysis addresses the first objective and builds on previous research on indoor air quality using data from one Green Housing Study site (Coombs 2016) by incorporating data from all three study sites.

The study hypothesis is that housing built to green standards has lower concentrations of environmental contaminants known to affect human health. Specifically, we hypothesize that the use of integrated pest management (IPM) results in fewer cockroaches and mice in the home, leading to lower concentrations of pesticides and lower levels of cockroach and mouse antigen than in conventional homes. We further hypothesize that green homes will be associated with reduced moisture and air pollutants because of better ventilation, leading to lower humidity, less reported mold, and lower levels of particulate air pollution (Figure 1).

2. Materials and Methods

2.1 Study Design

The Green Housing Study was a repeated-measures, 12-month prospective cohort study. The study enrolled children from three study sites; New Orleans, Louisiana; Boston, Massachusetts; and Cincinnati, Ohio. Children ages 7–12 years, with parent-reported doctor diagnosed asthma experiencing asthma-related symptoms (wheezing or night-time awakenings) during the previous 6 months were eligible for the study. An additional criterion for eligibility was living (defined as sleeping in the home on average 7 nights per week) in a HUD-subsidized home. Cities eligible for the Green Housing Study must have had one or more housing developments with a HUD-funded green renovation and have a high prevalence (greater than the national average) of childhood asthma.

A convenience sample of caregivers of children with asthma was recruited between September 2011 and March 2014. The target sample size was 192 households, 64 from each study site (32 green, 32 control). Written consent and assent were obtained from each caregiver and child, respectively, before any data collection. The study was reviewed and approved by CDC's Institutional Review Board (IRB) and the IRBs of Tulane University School of Public Health and Tropical Medicine and Harvard T.H. Chan School of Public Health.

2.2 Data Collection

Participants were followed for 12 months. Environmental, survey and biologic data were collected by experienced research staff trained in data collection protocols during three home visits occurring at baseline, 6 months, and 12 months.

2.2.1 Green and Non-green Housing—A housing development was classified as a green housing development if, at a minimum, the development was constructed or rehabbed using low volatile organic compound (VOC) materials and used integrated pest management (IPM). Developments were allowed to have additional green building components. Table 1 describes the components of green housing for included properties. In addition to low VOC materials and IPM, all properties were renovated using green building principles with an emphasis on improving indoor environmental quality, through an emphasis on comprehensive air sealing and insulation and use of heating and cooling systems meant to provide moisture control and improved air quality. All sites met recognized green building certification standards with Boston and Cincinnati obtaining LEED and New Orleans Enterprise Green Community certification.

Renovations in Boston and Cincinnati occurred on a rolling basis. The renovations occurred from 2010 to early 2011 in Boston and in 2011 to early 2012 in Cincinnati. In New Orleans, housing complexes were newly constructed and completed in 2011 and 2012.

Control homes were HUD-subsidized multi and single-family housing and housing choice voucher homes which were not built with low VOC materials, and which were not currently using building-wide IPM. In New Orleans and Boston, control homes were a mix of multifamily and housing choice voucher homes; in Cincinnati all control homes were multifamily housing.

2.2.2 Environmental measures

Air Pollution.: The level of particulate matter ≤2.5 μm ($PM_{2.5}$) and black carbon in the home was measured for a sampling period of up to 5 days at baseline and each follow-up visit. Single-stage Personal Modular Impactors (SKC, Inc., Eighty-Four, PA) connected to AirChek200 (Model 200–2002; SKC, Inc, Eighty-Four PA) pumps were placed in the child's primary sleeping area at a height of 0.6–1.5 meters. Integrated samples were collected on 37 mm, 2.0 μm pore-size PTFE membrane filters at a flow rate equal to 3 L/min. Pre-and post-calibration were conducted before the start of sampling and checked immediately after sampling with a BIOS DryCal DC-2 flow meter (SKC, Inc., Eighty-Four, PA).

The filters were analyzed for $PM_{2.5}$ and black carbon content at the Lamont-Doherty Earth Observatory following standard protocols for PTFE filters (Grass et al. 2010; Yan et al. 2011) Briefly, after equilibration for at least 24 hours in a temperature- and humidity-controlled chamber, filters were statically discharged via polonium sources and weighed on a microbalance inside the chamber. Two reference weights and one internal lab filter were measured every weighing session. A minor correction was made to all filters for differences in filter buoyancy due to atmospheric pressure difference pre- and post-measurement. The mass concentration of black carbon on the $PM_{2.5}$ filters was measured using a multi-wavelength integrating sphere method (Yan et al. 2011). The method uses a balanced deuterium and tungsten-halogen light source (DH-2000-BAL), an integrating sphere (ISP-50–8-R), a laboratory-made filter holder, and an Ocean Optics USB4000-VIS-NIR miniature fiber-optic spectrometer. $PM_{2.5}$ and black carbon were modelled as continuous variables in all analyses. The 5-day cumulative concentration of $PM_{2.5}$ and black carbon was calculated as the total amount of $PM_{2.5}$ and black carbon collected, divided by volume of air sampled over the collection period, with results reported as micrograms per cubic meter (μg/m^3).

Temperature and Humidity.: During day 1 and day 5 of each home visit, the temperature and humidity level was assessed in the living room using a portable thermohygrometer. The average of the two measurements was used as the measure of temperature and humidity level in the home during the sampling period.

Pest Allergens.: Cockroach (Bla g 2) and mouse (Mus m 1) antigen levels were assessed at each time point. Vacuum dust samples were collected from each child's sleeping area. Sample collection was performed using a standardized protocol developed by CDC. The mattress and pillows associated with the upper half of the bed (near the breathing zone) were vacuumed for 3 minutes. After sampling, each filter was sealed in a sterile plastic tube and stored at −20°C until analysis. Frozen dust samples were transported to the laboratory at CDC for processing. Samples were sieved, weighed, and aliquoted by CDC's National Institute for Occupational Safety and Health laboratory. Allergens were analyzed at Columbia University and Indoor Biotechnologies using commercially available immunoassays (ww.inbio.com). Cockroach and mouse allergen levels were modelled as dichotomous variables, detected vs non-detect, in all analyses (detection limit: cockroach = 0.02 μg/g, mouse = 0.0002 μg/g).

Mold.: The presence of mold in the home was assessed by participant report or visual observation by study staff. At each home visit, participants were asked "During the past 6 months, have you smelled or seen any mold in the home?" and study staff conducted a visual inspection of the entire home. If mold was observed, it was recorded. A positive response to the question by either the participant or staff was coded "yes" in all analyses.

Pesticides.: Pyrethroid (permethrin) dust levels were used as a measure of environmental pesticide exposure. Dust samples were collected by wiping two 12-inch square sections of the floor along the baseboard in the kitchen roughly 2–5 feet apart and preferably in less-disturbed corners of the room. Samples were gathered on gauze squares wetted with isopropanol and analyzed using gas chromatograph/mass spectrometry (GC/MS) and high-performance liquid chromatography/mass spectrometry (HPLC/MS) at the Wisconsin Occupational Health Laboratory with a calibration range of 0.2–10 μg per sample. Common pyrethroid (cis- and trans-permethrin, cyfluthrin), concentrations were measured in each dust sample. Pesticide levels were modelled as a dichotomous variable detected vs non-detect in all analyses.

Household Characteristics.: Household data were collected at the baseline visit. Data included participant activities (e.g., pesticide use) and characteristics of the home (household size, tenure, household income, etc.). In addition, a standardized questionnaire was administered by field staff at the end of each 5-day sampling period to gather information on occupant behavior during air sampling. The questionnaire included information about tobacco smoking, opening of windows and doors, the amount of time spent cooking, the use of candles or other combustion sources, and use of ventilation while cooking. These data were analyzed to determine if occupant activities had an effect on $PM_{2.5}$ and black carbon levels.

2.3 Statistical Analyses

Descriptive statistics were provided for all categorical and continuous variables for green housing status and environmental outcomes. Those include medians and ranges for continuous variables, and frequencies and percent for categorical variables. Differences between green and non-green homes at baseline were assessed using the Wilcoxon signed rank test for continuous variables and chi-square or exact tests for categorical variables.

The reliability of each environmental measurement was assessed across the 12-month follow-up. For $PM_{2.5}$, black carbon, temperature, humidity, and allergens (Bla g 2 and Mus m 1) the intra-class correlation coefficient (ICC) was calculated using a one-way random effects model to estimate within-person variance in each outcome over time: baseline, 6 months, and 12 months. For dichotomous variables Cochran's Q test was used to determine if responses were equal across the three time points.

To examine differences in environmental outcomes between green and non-green housing, unadjusted and adjusted regression models were developed separately for each outcome ($PM_{2.5}$, black carbon, temperature, humidity, cockroach and mouse allergens, mold, and pesticide). Regression analyses were conducted using generalized estimating equations (GEE) with clustering by site and unstructured correlation to account for the repeated measures design. In these models $PM_{2.5}$ and black carbon were natural log-transformed to normalize. For dichotomous variables, the distribution was assumed to be binomial. Results of GEE are reported as odds ratios (OR) and 95% confidence intervals (CI) for categorical outcomes and mean difference (β) and 95% CI for continuous variables.

To control possible confounding, household characteristics and occupant behaviors were examined at each home visit. Those that were associated ($p<0.1$) with both green housing and the environmental outcome in GEE analysis were included in multivariable models if they were not also mediators of the relationship between housing type and the environmental outcome. To account for temporal and geographic differences, site and season were chosen *a priori* to be included in all adjusted models. All analyses were performed using SAS (version 9.4; Cary, NC).

3. RESULTS

One hundred sixty-two households were recruited into the study (83 green and 79 non-green). New Orleans enrolled 35 green and 33 non-green homes, Boston enrolled 20 green and 29 non-green homes, and Cincinnati enrolled 28 green and 17 non-green homes. Homes were assessed at three time points, for a total of 449 observations. All of the included green housing developments exceeded the inclusion criteria of IPM and use of low VOC paint. Table 1 lists the specific characteristics of the green housing developments included in the study.

Table 2 and Supplemental Table 1 detail household characteristics at baseline. Most homes (91%) had an annual household income of less than $25,000, with 49% reporting an annual income of less than $5,000. The average household size was four inhabitants (IQR 3–5). The type of home (single family vs multifamily) varied between green and non-green homes. Residents of non-green homes were evenly split between single family and multifamily homes, while the majority of green housing (57%) was multifamily. There were significant differences between the season in which home visits were performed in green and non-green homes. Baseline visits for green homes were more likely to occur during spring (OR = 2.27, 95% CI = 0.96–5.36) and fall (OR = 1.45, 95% CI = 0.62–3.40) compared with visits to non-green homes. Therefore, in addition to site, all models were adjusted for the season in which sampling was performed. The average level of $PM_{2.5}$ over the study period was 28.4 μg/m^3. The average level of black carbon over the study period was 0.93 μg/m^3 (Supplemental Table 2).

Table 2 lists several participant activities that could have affected levels of $PM_{2.5}$, black carbon, and other environmental outcomes during the 5-day sampling periods. One third of participants (32%) reported smoking in the home, 45% reported opening the window for more than 1 hour a day, 35% reported that the air conditioner was on, and 29% reported having the heat on. During the sampling period, 81% reported cooking for more than 1 hour per day and 13% reported burning candles. No significant differences were found between green and non-green homes for any activities.

Table 3 presents a longitudinal examination of contaminant levels in the homes. Medians and standard deviations or interquartile ranges (for continuous outcomes) at baseline, 6 months, and 12 months are presented. To gain insight into the degree of variability in contaminant level over the year of follow-up we performed tests of reliability for the overall population and by green housing status. For air pollutants, $PM_{2.5}$ showed moderate reliability overall (ICC = 0.52) in green (ICC = 0.53) and non-green (ICC = 0.52) homes. In contrast, black carbon showed poor reliability (ICC = 0.06) overall and by green housing status (green ICC = 0.05; non-green ICC = 0.07). Not unexpectedly, temperature, humidity, and pest allergen levels also showed poor reliability (ICC < 0.5; Cochrane’s Q $p < 0.05$) across time. Detection of permethrin in dust samples in non-green homes and reporting mold in green homes were consistent across the year of follow-up (Cochrane’s Q $p = 0.14$ and 0.07, respectively).

We also examined the proportion of bed dust cockroach and mouse antigen samples that were above recommended health thresholds (Bla g 1 > 0.035 μg/g, Mus m 1 > 0.50 μg/g, respectively) (Chew 2003, Mitchell 2012) in Figure 2. We found substantial variation over the year of follow-up. We also found that, at each time point, cockroach antigen concentrations in green homes were lower than levels in non-green homes. However, mouse antigen concentrations did not differ between green and in non-green homes. When pest antigen level was treated as a continuous variable, results were consistent (data not shown).

Table 4 presents the results of the regression analysis. In unadjusted models, green housing was associated with statistically significantly lower concentration of black carbon ($\beta = -0.19$, 95% CI = −0.02 to −0.37, $p = 0.04$); pesticides (permethrin) (OR = 0.48, 95% CI = 0.28–0.80, $p = 0.01$); and reported mold (OR = 0.30, 95% CI = 0.14–0.62, $p = 0.002$). We also found that less cockroach antigen (Bla g 2) was detected in bed samples of green homes (OR = 0.62, 95% CI = 0.35–1.08, $p = 0.08$), although this difference was not statistically significant. In multivariable models adjusted for study site and season, results were essentially unchanged. In green homes, levels of black carbon ($\beta = -0.22$, 95% CI = −0.06 to −0.38, $p = 0.01$); detected permethrin (OR = 0.28, 95% CI = 0.15–0.49, $p < 0.0001$), and reported mold (OR = 0.29, 95% CI = 0.13–0.68, $p = 0.003$) were significantly lower than in non-green homes. The proportion of bed samples with cockroach antigen detected was lower in green versus non-green homes (OR = 0.59, 95% CI = 0.33–1.08, $p = 0.09$). However, consistent with the unadjusted results, this difference did not reach statistical significance. An unexpected finding was that in adjusted models, mouse antigen (Mus m 1) was 68% more likely to be detected (OR = 1.68, 95% CI = 0.99–2.85) in green versus non-green homes. The results for cockroach and mouse antigen levels were unchanged when treated as a continuous variable (data not shown). To investigate the potential source(s) of particulate matter and black carbon, we developed multivariable models using stepwise variable selection to maximize the marginal R^2, adjusting for site. We found that 68% of $PM_{2.5}$ was explained by dwelling type and indoor smoking. In contrast, 42% of black carbon was explained by the variables, venting while cooking (40%) and use of a gas stove (2%).

4. Discussion

Green building practices have been widely adopted around the world in response to the need for more environmentally sustainable building processes. The green building movement emerged in the 1990s and has since gained international momentum (Wuni 2019). Data provide evidence of reductions in energy consumption resulting from changing building practices but the effects of those changes on indoor air quality and related contaminants, is still unresolved (Lim 2021, Mannan 2021). The principles of green building design are at the intersection of environmental and human health (Willand 2017). From the environmental perspective, green building approaches emphasize energy efficiency by reducing air leakage, creating a tighter building envelope. From the health perspective, green building emphasizes improved indoor air quality and sustainability by using natural and lower toxicity materials (reducing chemical exposure), improved ventilation (reducing moisture and indoor air pollution), and use of integrated pest management (reducing pest allergen and pesticide exposure) (Xiong 2015).

The economic benefits of green housing include energy savings (Brod 2020). However, reduced air exchange rates could lead to increased concentrations of indoor-sourced pollutants if ventilation is inadequate or if lower toxicity products are not used in the design and maintenance of the home (Ferguson 2020, Underhill 2018, Broderick 2017). Additionally, green building practices might not lead to improved health if human activities (particularly smoking) contribute more to indoor air pollution than does pollutant infiltration from outdoor sources or from the type of building materials used in construction (Moreno-Rangel 2020, Coombs 2016, Tunno 2015). To address this data gap, we compared housing built using green components and practices, conducting a repeated measures observational cohort study where we did not single out individual green components. This allowed us to investigate the green housing *framework* in a real world setting rather than individual building features.

In this sample of 162 homes, primarily of families with low-income status, we found in adjusted models that houses built to green standards were associated with significantly lower concentrations of black carbon and permethrin, and significantly less reported mold than were non-green homes. Green homes also were associated with reduced concentration of cockroach and mouse allergen, although these reductions did not reach statistical significance. We found no differences in $PM_{2.5}$ or humidity by green housing status. In longitudinal models, we found that the level of $PM_{2.5}$, regardless of housing type, was relatively stable across the year of follow-up, as were reported mold in green housing and permethrin level in non-green homes. The levels of black carbon and pest antigen, however, were not stable.

The difference in the concentration and variability over the year between $PM_{2.5}$ and its constituent, black carbon, is interesting. There might be several explanations for this. First, sources of indoor air pollution include infiltration from outdoors and sources that originate indoors. They are also influenced by occupant activities. Several studies have shown that a greater proportion of indoor black carbon concentration originates from outdoor rather than indoor sources (Götschi 2022, Gruzieva 2020) and our data are consistent with these findings. In our cohort, indoor activities related to $PM_{2.5}$ and black carbon varied. Adjusting for site, we found that 42% of black carbon concentration was explained by the variables, venting while cooking and use of a gas stove. Counterintuitively, venting while cooking was associated with an increase in BC. This may have been due to participants using the vent as a result of smoke and not as a preventative measure to reduce smoke. In addition, the type of vent (external vs internal) was not assessed and is a limitation of the analysis. In contrast, adjusted for site, 68% of $PM_{2.5}$ was associated with multifamily dwelling (versus single family or duplex) and smoking indoors.

We hypothesize that green building practices, which emphasize a tighter building envelope and ventilation, were responsible for lower levels of black carbon in green homes. We further hypothesize that $PM_{2.5}$ did not differ between green versus non-green homes because occupant behavior (smoking) and building characteristics (multifamily vs single/duplex family dwelling), rather than features associated with green building practices, were the primary factors associated with $PM_{2.5}$ concentration. This contrasts with a previous study that showed lower $PM_{2.5}$ levels in green homes where indoor smoking was prohibited

(Colton 2014). In our cohort, the correlation between $PM_{2.5}$ and black carbon was low overall and at each time point (correlation coefficient 0.48, data not shown), adding further support to this supposition. The finding that $PM_{2.5}$ is unrelated to green building status, in contrast to other contaminants (e.g., PM_{10}, CO_2 and volatile organic compounds), was also found in a recent study in South Korea (Lim 2021). These findings highlight the need for further research into the specific components of fine particulate air pollution.

Although participant-reported pesticide use was higher in green versus nongreen homes, an important finding is that when using a quantitative assessment of exposure, overall and at each time point, the level of cockroach antigen was lower in green versus non-green homes (although this difference did not reach statistical significance) and the proportion of homes in which permethrin, an insecticide widely used for cockroach control, was detected was also lower in green versus non-green homes. Taken together, this suggests that the use of IPM, a feature of all enrolled green homes, might have contributed to fewer cockroaches and less use of pesticides. The finding that mouse antigen levels were not significantly lower in green homes may be because of low levels in both homes. Or it may be because of a greater focus on cockroach control in the implementation of IPM. IPM often includes the targeted use of pesticide baits for cockroach control in addition to the sealing of harborages and openings to limit the movement of pests both into structures and between rooms; however, this may not be sufficient to control house mice infestations in rehabbed buildings. Finally, the finding that reported mold was significantly lower in green homes and reported to be stable over the year also provides evidence that improved ventilation might have resulted in drier homes or that replacement of mold-contaminated furnishings could have removed visible and hidden mold, pests, and pesticides. Given the strong association between cockroach and mold exposure and childhood asthma (Rabito 2017, DeMango 2016, Jaakkola 2005), if confirmed, this would be an important benefit of green housing design.

Strengths of the study include the relatively large sample size, the multi-city sample, and the repeated measures design allowing the assessment of season and reliability over one year. Despite the strengths of the study, there are several limitations which warrant consideration. These include differences in the number and type of green building characteristics across study sites and the lack of a recently non-green renovated comparison group. Regarding the former, there is no standard definition for green housing, however, it is generally accepted that building to green standards includes engineering and materials that improve indoor environmental quality and in particular indoor air quality through improved ventilation and insulation (Fisk 2020, Steinemann 2017). Although the specific green components in each development may differ, we believe all properties categorized as green include such features, and importantly, were built or renovated with the intention of being considered ‘green’. The study tests the green building *framework* as used in real world settings, rather than individual building components.

A limitation of the study is that we did not have a recently non-green (conventionally) renovated comparator group, nor did we have information on the date of last major renovation or construction in non-green homes beyond those occurring in the previous six months. As a result, we cannot discern whether a newly built/renovated home without green components would have similar effects as those found in this study. Conventionally renovated homes with components such as sealing cracks/crevices, new windows, flooring and HVAC systems, and exhaust fans could have lower levels of pests, molds and improved ventilation. While we can only report the results of green renovation, conventional renovation remains an area for exploration.

Finally, this paper does not include results of VOC measurements in study homes, a topic of interest because of the use of lower VOC-emitting materials in the green study homes. The results of VOCs analysis will be reported in a future publication.

5. CONCLUSION

Housing quality is a modifiable risk factor that can have beneficial population-level health effects. However, before specific housing interventions can be recommended as a way to improve health, the impact on contaminant concentrations should be carefully examined. This analysis provides quantitative evidence of the possible benefits of incorporating green building practices on the level of numerous environmental contaminants known to be associated with human health. Further research directly comparing green renovated to conventionally renovated housing is needed to confirm these findings.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Highlights

- Quantitative evidence of green housing on environmental contaminant level is unclear.
- Black carbon, mold, pest antigen, and pesticide levels were lower in green housing.
- $PM_{2.5}$ concentration did not differ between green versus non-green housing.
- The factors most strongly associated with f $PM_{2.5}$ were multifamily housing and smoking.
- Occupant behavior should be considered when assessing the effects of green housing.

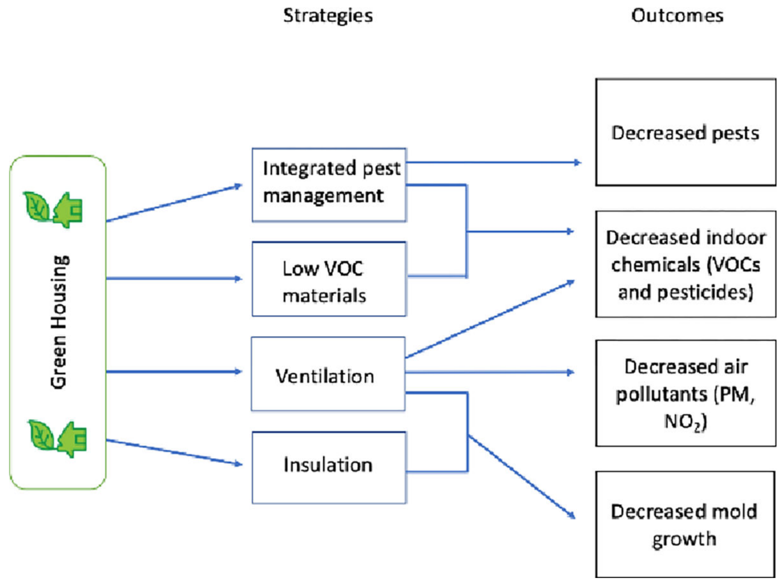
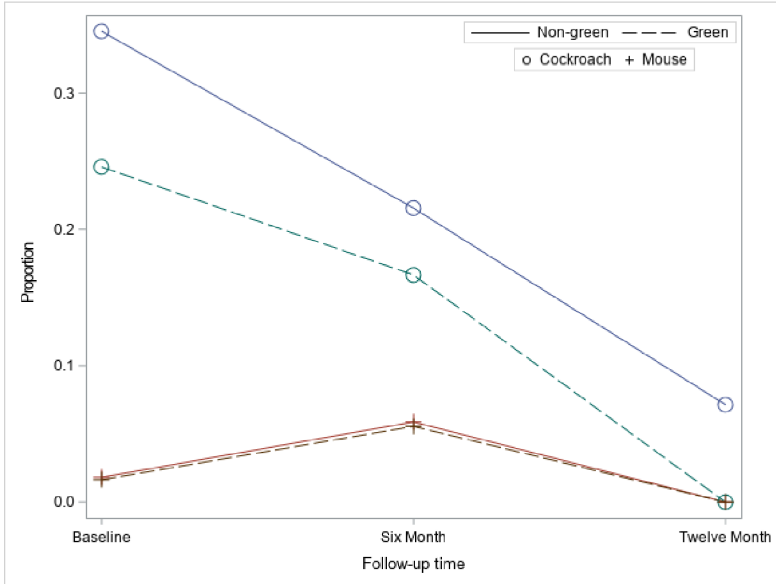


Figure 1.

Conceptual Framework of the Association between Green Housing and Environmental Outcomes



*Bla g 1 > 0.035 ug/g; Mus m 1 > 0.50 ug/g

Figure 2.

Proportion of children's beds with cockroach (Bla g 2) and mouse (Mus m 1) allergen above the clinically significant threshold

Table 1.

Specific green components of housing developments designated "green"

Primary study sites	Green components
New Orleans	Certified Enterprise Green Community Low VOC materials, energy efficient central forced-air ventilation system (in accordance with ASHRAE62.2–2010), high-efficiency heating and cooling systems engineered for moisture control and improved indoor air quality, thermal enclosure System including comprehensive air sealing, insulation, and high-performance windows, bathroom fans that turn on automatically, kitchen exhaust vents, clothes dryer exhaust vented to outdoors, mold resistant surfaces (bath, kitchen, laundry, floors), IPM
Cincinnati	LEED Platinum Certification Low VOC materials, whole house insulation, bathroom exhaust fans that are turned on by the resident, energy efficient central heating/cooling systems with programmable thermostats, energy-efficient windows, doors, lighting, IPM
Boston – Study site 1	LEED Platinum Certification Low VOC materials, whole-house insulation ("shell" covering the entire original building), insulated reflector roof, high-efficiency windows, lighting, energy-efficient appliances, IPM
Boston – Study site 2	LEED Platinum Certification Low VOC paint, high-efficiency, gas-fired hydronic heat and hot water, heat-recovery ventilator or energy-recovery ventilator that continuously exhausts air outdoors from bathrooms, cellulose insulation and high-performance windows, high albedo roofs and fiberglass roof insulation, IPM

VOC = volatile organic compound(s); IPM = integrated pest management; LEED = Leadership in Energy and Environmental Design

Table 2.

Characteristics of homes and participant activities during environmental sampling at baseline by housing type (green vs non-green); N = 162

	Total	**Green**	**Non-green**	**OR (95% CI)**	**p**
	N = 162	**N = 83 (51.2%)**	**N = 79 (48.7%)**	**Green vs Non-green**	
	Median (IQR)	Median (IQR)	Median (IQR)		
Household size (# people)	4 (3–5)	4 (3–5)	4 (3–5)		0.33
Tenure (years)	2 (1–5)	2 (0–4)	3 (1–6)		**0.03**
	n (%)	n (%)	n (%)		
Annual household income					
<$25,000	150 (92.6)	75 (90.4)	75 (94.9)	0.52 (0.15–1.81)	0.29
≥$25,000	11 (6.8)	7 (8.4)	4 (5.1)	REF	
Refused	1 (0.6)	1 (1.2)	0 (0)		
Type of home					
Single family	69 (42.6)	29 (34.9)	40 (50.6)	REF	
Multifamily	86 (53.1)	47 (56.6)	39 (49.3)	1.66 (0.87–3.15)	0.12
Missing	7 (4.3)	7 (8.4)	0 (0)	—	
Home Characteristics					
Stove type					0.37
Electric	80 (49.4)	42 (50.6)	38 (48.1)	REF	
Gas	75 (46.3)	34 (41.0)	41 (51.9)	1.33 (0.71–2.51)	
Missing	7 (4.3)	7 (8.4)	0 (0)	—	
Bathroom Exhaust Fan					**0.01**
Yes	138 (85.2)	73 (94.8)	65 (82.3)	3.93 (1.23–12.54)	
No	18 (11.1)	4 (4.8)	14 (17.7)	REF	
Missing	6 (3.7)	6 (7.2)	0 (0)		
Exhaust Fan Use					0.11
Always	72 (44.4)	39 (47.0)	33 (41.8)	2.27 (1.01–5.00)	
Sometimes	46 (28.4)	25 (30.1)	21 (26.6)	1.01 (0.48–2.12)	
Never	38 (23.5)	13 (15.7)	25 (31.7)	REF	
Missing	6 (3.7)	6 (7.2)	0 (0)		
Any water damage					0.11
Yes	25 (16.5)	9 (11.7)	16 (21.3)	0.49 (0.20–1.19)	
No	127 (78.40)	68 (81.9)	59 (74.7)	REF	
Missing	10 (6.2)	6 (7.2)	4 (5.1)		
Carpet changed *					0.29
Yes	14 (8.6)	5 (6.5)	9 (11.3)	0.54 (.17–1.69)	
No	142 (87.7)	72 (86.7)	70 (88.6)	REF	
Missing	6 (3.7)	6 (7.2)	0 (0)		

	Total	**Green**	**Non-green**	**OR (95% CI)**	**p**
	N = 162	**N = 83 (51.2%)**	**N = 79 (48.7%)**	**Green vs Non-green**	
Renovation *					**<.0001**
Yes	41 (25.3)	32 (47.8)	9 (13.6)	5.79 (2.47–13.56)	
No	92 (56.8)	35 (42.2))	57 (72.2)	REF	
Missing	29 (17.9)	16 (19.3)	13 (16.5)		
Season sampled					**0.04**
Winter	42 (25.9)	19 (22.9)	23 (29.1)	REF	
Spring	46 (28.4)	30 (36.1)	16 (20. 3)	2.27 (0.96–5.36)	
Summer	30 (18.5)	10 (12.0)	20 (25.3)	0.60 (0.23–1.60)	
Fall	44 (27.2)	24 (28.9)	20 (25.3)	1.45 (0.62–3.40)	
Participant activities during environmental sampling					
Smoking in home	52 (32.1)	29 (34.9)	23 (29.1)	1.36 (0.69–2.64)	0.37
Cooking ≥1hr/day	132 (81.5)	63 (75.9)	69 (87.3)	0.51 (0.21–1.24)	0.13
Vent while cooking	106 (65.4)	55 (66.3)	51 (64.6)	1.19 (0.57–2.47)	0.64
Burning candles	21 (13.0)	11 (13.3)	10 (12.7)	1.10 (0.44–2.76)	0.84
Open windows ≥1 hr/day	73 (45.1)	37 (44.6)	36 (45.6)	1.00 (0.54–1.88)	0.99
Use air conditioner ≥1 hr/day	57 (35.2)	26 (31.3)	31 (39.2)	0.74 (0.39–1.43)	0.37
Use heat ≥1 hr/day	47 (29.0)	28 (33.7)	19 (24. 1)	1.70 (0.85–3.41)	0.13

* Previous 6 months

Table 3.

Environmental outcomes at each time point by green housing status, n = 449

	Baseline				Month 6				Month 12						
	Green (N = 83)		Non-Green (N = 79)		Green (N = 78)		Non-Green (N = 67)		Green (N = 77)		Non-Green (N = 65)				
													ICC		
	n	Median (IQR)	n	Median (IQR)	n	Median (IQR)	n	Median (IQR)	n	Median (IQR)	n	Median (IQR)	Green	NG	All
$PM_{2.5}$ (μg/m^3)	79	17.43 (10.69–47.88)	73	16.58 (7.71–30.69)	73	11.75 (7.81–33.04)	64	14.63 (8.87–25.85)	74	18.55 (11.09–34.84)	63	13.49 (8.55–31.34)	0.53	0.52	0.52
Black carbon (μg/m^3)	81	0.90 (0.58–1.42)	71	0.89 (0.63–1.23)	72	0.57 (0.29–1.02)	63	0.59 (0.39–0.91)	73	0.71 (0.44–0.84)	62	0.86 (0.58–1.39)	0.05	0.07	0.06
Temperature (°F)	83	73.04 (71.00–75.50)	79	73.90 (70.50–76.50)	75	74.50 (72.60–77.15)	67	74.50 (72.50–79.20)	76	72.77 (71.25–75.03)	65	73.50 (71.50–77.00)	0.03	0.02	0.02
Humidity (%)	83	50.00 (41.50–56.50)	79	46.55 (39.00–53.50)	75	51.00 (36.00–57.00)	62	49.75 (40.00–56.00)	74	48.98 (38.00–53.00)	65	49.50 (43.50–53.00)	0.17	0.18	0.18
													Cochrane's Q p-value		
	n	n (%)	n	n (%)	n	n (%)	n	n (%)	n	n (%)	n	n (%)	Green	NG	All
Mouse detected[a]	61	57 (93.44)	55	51 (92.73)	54	33 (61.11)	51	27 (52.94)	54	33 (61.11)	51	27 (52.94)	0.004	0.02	<0.0001
Cockroach detected[b]	61	21 (34.43)	55	27 (49.09)	54	9 (16.67)	51	11 (21.57)	54	9 (16.67)	51	11 (21.57)	0.0001	0.01	<0.0001
Report mold	81	10 (12.35)	79	22 (27.85)	78	2 (2.56)	67	10 (14.93)	77	4 (5.19)	65	6 (9.23)	0.07	0.01	0.001
Permethrin detected[c]	83	21 (25.3)	79	37 (46.80)	77	28 (36.60)	68	32 (47.10)	77	29 (37.70)	64	36 (56.30)	0.03	0.14	0.01

[a] Mus m 1; LOD = 0.0002 mcg/g

[b] Bla g 2; LOD = 0.02 mcg/g

[c] LOD = 0.2 mcg/sample

ICC = intraclass correlation coefficient; IQR = interquartile range; NG = non-green

Table 4.

Unadjusted and adjusted associations between green housing and environmental outcomes, generalized estimating equations

	Unadjusted			Adjusted[a]		
	No.	**β (95% CI)**	**p**	**No.**	**β (95% CI)**	**p**
PM (ln)	426	0.17 (−0.08 – 0.41)	0.19	426	0.04 (−0.19–0.26)	0.74
Black carbon (ln)	422	−0.19 (−0.37– -0.02)	**0.04**	422	−0.22 (−0.38 – -0.06)	**0.01**
Humidity (%)	438	−0.23 (−2.69 – 2.22)	0.85	438	0.99 (−0.48–2.47)	0.19
Mouse allergen, Mus m 1	300	−0.04 (−0.13 – 0.04)	0.32	300	−0.04 (−0.13–0.05)	0.37
Cockroach allergen, Bla g 2	300	−0.19 (−0.43 – 0.05)	0.11	300	−0.24 (−0.52–0.04)	0.10
		OR (95% CI)			**OR (95% CI)**	
Mouse detected	300	1.38 (0.81–2.35)	0.24	300	1.68 (0.99–2.85)	0.06
Cockroach detected	300	0.62 (0.35–1.08)	0.08	300	0.59 (0.33–1.08)	0.09
Report mold	447	0.30 (0.14–0.62)	**0.002**	447	0.29 (0.13–0.68)	**0.003**
Permethrin detected	448	0.48 (0.28–0.80)	**0.01**	448	0.28 (0.15–0.49)	**<0.0001**

[a]All models adjusted for site and season; ln PM additionally adjusted for tenure; bold indicates statistically significant $p < 0.05$; No. indicates the number of observations.