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# Weatherization impacts and baseline indoor environmental quality in low income single-family homes

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A B S T R A C T

Understanding the impact of energy efficiency measures on Indoor Environmental Quality (IEQ) is important to building science and public health. Data were collected at three North Carolina locations for $CO_2$, CO, $NO_2$, temperature, RH, formaldehyde, radon, $PM_{2.5}$, $PM_{10}$, particle counts, household characteristics, and weather in 69 homes, before (PRE) and after (POST) weatherization, and in 13 control homes. Comparison of IEQ data to indoor and ambient air guidelines showed the number of homes with acceptable IEQ was the same or greater after weatherization for all parameters except temperature, and PM in smoking homes. POST compliance was over 90% for $CO_2$, CO, Radon, and $NO_2$ in all homes, and RH and PM in non-smoking homes. Overall POST compliance for formaldehyde was 75%, and in smoking homes 6%, 24%, and 78% for $PM_{2.5}$, $PM_{10}$, and RH, respectively. Wilcoxon test results, at significance level <0.05, showed decreased POST levels for radon in heating season homes, RH in heating season homes without pets, 1.0μm and 2.5μm particles in homes without pets, and increased levels of formaldehyde in cooling season homes without pets, particles >1.0μm and $PM_{10}$ in heating season homes with pets, and 10μm particles in cooling season homes. Chi-Square analysis identified relationships between season and CO, $NO_2$, and formaldehyde. Positive correlations were identified for pets and particles >1.0μm, smokers and 0.3μm and 0.5μm particles, heating season and increasing formaldehyde, and negative correlation for $CO_2$ and ventilation.



## 1. Introduction

### 1.1. Statement of problem

The combined energy consumption by commercial and residential buildings constitutes 41% of the entire United States (U.S.) energy budget, making it a prime target for energy reduction to reach national energy security and climate change mitigation goals [1]. Over the past 38 years, 7 million low-income households have been weatherized. From 2009 to 2012 through the American Reinvestment and Recovery Act, more than 750,000 homes received weatherization services in the U.S., 15,510 of which were in North Carolina (NC) where this study was conducted [2]. While the focus on saving energy has many benefits, it is important to understand potential impacts of energy efficiency measures on Indoor Environmental Quality (IEQ) in order to ensure the well-being of building occupants.

Weatherization measures that include air sealing combined with adequate ventilation has the potential to improve indoor comfort and air quality [3], but sealing the envelope too tightly and/or failure to properly balance pressure differentials, particularly in homes with no provisions for controlled ventilation, can lead to conditions that increase the potential for moisture problems and contaminant accumulation [4]. There may be other health hazards related to inherent characteristics of building materials used for energy conservation and occupant generated contaminants that are exacerbated by reduced ventilation rates [5], including increased

*Abbreviations:* ACH = Air Changes per Hour, CAA = Community Action Agency; CNTRL = Control Home, CS = Cooling Season; CST = Coastal study location, HCHO = Formaldehyde; HS = Heating Season, MNT = Mountain study location; PDT = Piedmont study location, POST = After Weatherization; PRE = Before Weatherization, WAP = Weatherization Assistance Program.

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levels of formaldehyde [6], VOCs [7,8], radon [9], and environmental tobacco smoke [10]. Replacing atmospherically vented combustion equipment with high-efficiency equipment, combined with air sealing, can lead to lower ventilation, change airflow patterns, and create pressure dynamics that can lead to intrusion of soil gases and radon [11].

Key environmental hazards associated with low-income housing, such as mold and moisture, combustion by-products, secondhand smoke, and inadequate ventilation can lead to cumulative exposure associated with increased risk of poor health [12]. Weatherization-eligible dwellings are often susceptible to poor indoor air quality conditions initially, and ventilation systems that are improperly designed, installed, maintained, and operated may have harmful effects on indoor air quality and climate [13]. In addition to the increased risk of poor IEQ in low-income housing, vulnerable populations that are particularly susceptible to the adverse health effects from air pollution include those with impaired health (especially reduced cardiopulmonary function), children with their greater activity and developing lungs [14], and the elderly who comprised the majority of our study participants.

The link between energy efficiency and lower heating bills is well established, and a wide range of potential positive and negative impacts on population health and the environment has been identified [15]. Although the evidence base is sufficient to infer the general impact of poor IEQ on health outcomes, specific information regarding the potential impact that energy efficiency measures may have on IEQ is not well documented for residential homes [16].

### 1.2. Study overview

This study investigates changes in IEQ that may be a result of energy-efficiency measures, by quantifying indoor environment parameters before and after weatherization in single-family, low-income housing in North Carolina's three distinct climate zone types that comprise approximately 40% of the contiguous United States [17].

- Warm-Humid [ZONE 3A] Location: Wilmington, NC, Atlantic coast (Coast = CST).
- Mixed-Humid [ZONE 4A] Location: Raleigh, NC, central Piedmont region (Piedmont = PDT).
- Cool-Humid [ZONE 5A] Location: Boone, NC, Appalachian Mountains (Mountain = MTN).

Data were collected for key housing-related health hazards, identified in the Healthy Homes Strategic Plan [18], and from outdoor weather monitoring equipment, home assessments, occupant interviews that did not include health questions, and daily activity logs. Eight IEQ parameters were monitored including temperature (Temp), relative humidity (RH), carbon monoxide (CO), carbon dioxide ($CO_2$), nitrogen dioxide ($NO_2$), formaldehyde (HCHO), particulate matter (PM) size counts and mass concentration, and radon. Outdoor weather data included temperature (Temp Out), relative humidity (Out Hum), wind speed and direction, maximum wind speed, rainfall, and barometric pressure. The null hypothesis being tested is that IEQ conditions are the same before and after weatherization. Specific objectives address the following interrelated questions that have implications for public health and building practitioners and researchers.

➢ What effect does weatherization have on the percentage of homes meeting acceptable IEQ criteria?
➢ In what percentage of homes is weatherization improving, worsening, or having no impact on IEQ?
➢ Are there statistically significant differences between pre- and post -weatherization IEQ conditions?
➢ Are there commonalities across homes that share similar IEQ outcomes?

## 2. Materials and methods

### 2.1. Study participants

Study participants were recruited through three NC community action agency (CAA) partners with ongoing WAPs to leverage services being provided to low-income households. The pool of participants was initially self-selected to households applying for weatherization services. Based on additional inclusion criteria (owner-occupied, single-story, no basement), eligible participants were identified and offered the opportunity to participate. A detailed consent form, approved by the Institutional Review Board at Appalachian State University, was reviewed for signature with homeowners who expressed interest in participating. Upon completion of data collection, participants were paid a $100 stipend.

A total of 92 participants were recruited, with 10 homes having a missing sampling period or invalid data, for an attrition rate of 11%. Paired pre-weatherization (PRE) and post-weatherization (POST) data were collected from 69 WAP homes for the data set considered to be an estimate of occupant exposure and used to determine IEQ compliance. In addition to the homes receiving WAP services, IEQ and weather data were collected in 13 volunteer "control" homes of University and CAA staff, 3–4 weeks apart (CNTRL1 and CNTRL2) with no intervening weatherization changes to the home. All control homes were non-smoking with 9 of 13 homes having no pets. Three-quarters (54) of the WAP homes received only the standard ventilation as prescribed by NC weatherization installation standards [19] and comprise the data used for PRE and POST comparisons. Additional household features for these homes are provided in Section 2.2.2. The remainder of the WAP homes (15) received a temporary alternative ventilation intervention, consisting of a programmable fan timer, after weatherization was completed. A first set of post-weatherization data in these homes was collected with the exhaust fan timer set to run during peak contaminant concentration periods. After data collection was completed, the standard WAP mechanical fan switch was permanently installed to complete the weatherization, and a second set of post-weatherization data was collected that is included in the IEQ compliance data set described above. Alternative ventilation homes had 10 of 15 non-smoking, and 7 of 15 no pet homes. Because the sampling timeline for the alternative ventilation households was different than the one used for the other 54 homes, these data were not included in the data set used for PRE and POST comparisons. Alternative ventilation methodology and results will be reported in a separate paper.

### 2.2. Data collection

Data were collected over a three-year period from December 2012 to April 2015. During this time period, weatherization standards required installation of continuous ventilation in all homes. In order to get representative samples of indoor air, IEQ monitoring was restricted to two seasons, summer cooling season (CS) and winter heating season (HS), when participants kept their windows and doors closed during both PRE and POST sampling periods. Due to a cooler summer climate and general lack of air-conditioning, only HS data were collected at the MTN location. Scheduling of data collection was coordinated with the ongoing CAA weatherization activities. Upon completion of an initial home assessment by