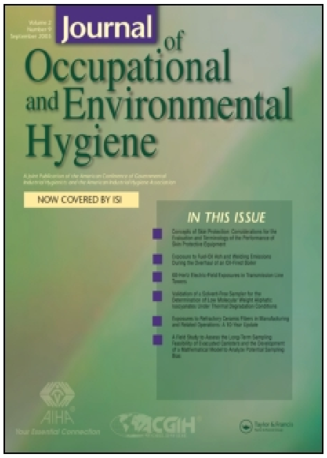

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Particle Resuspension During the Use of Vacuum Cleaners on Residential Carpet

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Vacuuming is generally considered to be an important activity with respect to the cleanliness of indoor environments but may lead to short-term resuspension of particulate matter and elevated particle mass in indoor air. Because resuspended particles often contain toxicants, such as lead and pesticides, or consist of biological agents that can trigger allergic reactions, it is important to understand the role of vacuuming on short-term variations in indoor particulate matter concentrations. The inhalation of particles during vacuuming events may affect adversely those whose occupation requires them to clean a wide range of indoor environments, from homes to schools and offices, as well as those who occupy those environments. In response, a series of 46 experiments was completed to determine time-variant concentrations of both PM_{10} and $PM_{2.5}$ during various vacuuming activities in 12 separate apartments. Experiments involved the use of two different non-HEPA vacuum cleaners and were completed with a vacuum cleaner activated (switched on) as well as deactivated (switched off). The latter was intended to provide insight on the potential for resuspension of particles by the mechanical agitation of vacuum cleaner movement across carpet. Separate experiments were completed also using "mock" vacuuming simulations, that is, walking on the carpet in a manner consistent with using a vacuum cleaner. Results are presented as incremental particulate matter concentration increases, relative to background (prevacuum) concentrations, and peak-to-background particle concentration ratios. Results indicate significant resuspension of PM_{10} mass during vacuum cleaning, with a mean time-averaged PM_{10} increase of greater than 17 $\mu g/m^3$ above background. Resuspension of $PM_{2.5}$ mass was determined to be small, that is, PM_{10} mass was dominated by particles greater than 2.5 μm. The frequency of vacuuming (between a 10-day standard frequency and several experiments at >24 days between vacuuming) had little influence on resuspended particle mass. Resuspension by mechanical agitation (rolling of vacuum cleaner across carpet) with the vacuum cleaner switched off was determined to be substantial, with a mean time-averaged (during vacuuming) PM_{10} increase of 35 $\mu g/m^3$ relative to background. Peak-to-background PM_{10} concentrations exceeded 6 for some experiments and averaged between approximately 3 and 4 for experiments when the vacuum cleaner was switched on.

Keywords carpet, cleaning, field measurement, particulate matter, resuspension, vacuuming

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INTRODUCTION

Human exposure to ambient (outdoor) particulate matter has been implicated in numerous health outcomes.[1−3] However, on average, Americans spend nearly 90% of their time in indoor environments,[4] and as such, indoor concentrations are potentially important contributors to human exposure to particles. Indoor activities such as cleaning can be significant particle sources that can elevate indoor concentrations. Nazaroff and Weschler[5] and references cited therein state that 3 million American workers are employed in cleaning functions and that, on average, U.S. adults clean for 20–30 min each day. In this article the authors explore the impact of one indoor cleaning activity, vacuuming, on indoor particle concentrations.

Vacuuming has been studied extensively as an intervention to improve hygiene and to decrease the frequency and severity of asthma, allergies, and other health outcomes. Several studies have shown the prevalence of allergens in house dust, including dust mite allergens *Der f1*, *Der p1*, or *Der p2*,[6−10] cat allergen *Fel d1*,[8,11,12] mouse allergen *Mus m1*,[13,14] and dog allergen *Can f1*.[8,12] Vacuuming, often in combination with other measures, has been shown generally to improve indoor air quality[15] and specifically to reduce concentrations of airborne dust mite allergen,[9,16] mouse allergen,[14] and endotoxins,[17] as well as decrease the prevalence of atopic eczema.[18]

Several researchers also have identified vacuuming as a source of particulate matter, including airborne allergens. For example, de Blay et al.[19] observed a significant increase in airborne *Fel d1* when vacuuming with two out of five tested vacuum cleaners. Further, Causer et al.[10] found that pile height and wear had a significant impact on ease of *Der f1* removal from carpet. Abt et al.[20] measured an increase of PM_{10} during vacuuming. Ferro et al.[21] measured a 0.19–0.45 mg/min vacuuming source strength, i.e., mass emission rate caused by resuspension of particles, for $PM_{2.5}$ and a 0.36–0.72 mg/min source strength for PM_5. Montoya and Hildemann[22,23] found elevated concentrations of dust, collected from a home with two cats, after vacuuming a carpeted surface, particularly for particles larger than 2.5 μm. Concentrations of 2.5–20-μm particles 5 min after a vacuuming event ranged from 0.25 mg/m^3 to 2.7 mg/m^3 and decreased substantially after three vacuuming events, suggesting depletion of the source. They also measured elevated levels of *Fel d1* in the resuspended particles after the vacuuming events. Long et al.[24] measured a maximum concentration during vacuuming events in nine homes of 6.5 μg/m^3 for $PM_{2.5}$ and volume concentrations of 0.06–6.7 μm^3/cm^3 above background. Thatcher and Layton[25] reported concentration ratios, defined as the particle mass concentration during vacuuming divided by particle mass concentration before vacuuming, of 1.2 for 0.5–1-μm particles to 29.5 for 10–25-μm particles. Lioy et al.[26] measured fine and ultrafine particle emissions from the motors of 10 vacuum cleaners (8 with and 2 without HEPA filters) and found emission rates of 6.2–176 μg/min for 0.3–3-μm particles. Afshari et al.[27] measured a source strength of 3.5–3.8 $\times$ 10^{10}particles/min for ultrafine particles from a single vacuum cleaner, with most of those emissions coming from the vacuum cleaner motor. Taken together, these results suggest that vacuum cleaners can be an important source of particulate matter and allergens in indoor environments.

In this article, the role of vacuuming on the resuspension of PM_{10} and $PM_{2.5}$ from carpeted floors is investigated. The authors explore the impact that timing between vacuuming events has on mass concentrations of airborne particles in order to assess the effect of event frequency on resuspension. The authors also explore the effects of particle resuspension by rolling a deactivated vacuum cleaner across carpet and by simulating foot-on-carpet activity in the absence of a vacuum cleaner. The results presented here can be used to assess the impact of these factors on human exposure during and after vacuuming events.

METHODS

Experimental Program

A series of 46 experiments was completed in 12 carpeted apartments over a 4-month period. Each experiment involved one of two vacuum cleaners or mock vacuuming events involving only foot-on-carpet contact. Experiments lasted 170 min and were completed in three stages: Stage 1 = 30-min background measurements; Stage 2 = 20-min vacuuming or mock vacuuming period; Stage 3 = 120-min postvacuuming period. For each stage, measurements were made of either PM_{10} (standard case) or $PM_{2.5}$ mass concentration, both at a height of 1 m above floor level in the middle of the living room being vacuumed.

Most experiments were completed with a standard 10-day period between vacuuming of an apartment, but nine experiments were completed with greater time periods between vacuuming events. Six experiments were completed to explore the degree of PM_{10} resuspension during the use of a vacuum cleaner without power; six additional experiments involved mock vacuuming without a vacuum cleaner.

Vacuum Cleaning Devices

Two popular vacuum cleaning devices were employed. Vacuum Cleaner A (VCA) was a 1-year-old 7-amp upright cleaner with a standard paper bag filter and brush roller. Vacuum Cleaner B (VCB) was a new 12-amp upright cleaner that included a brush roller and triple filter system comprising a "micro" paper bag filter and two filter pads. The manufacturer of VCB claimed >99% capture of particles greater than 5 μm in aerodynamic diameter.

Apartment Characteristics

Twelve different apartments in Austin, Texas, were used in this study. Each apartment was occupied by two, nonsmoking university students without pets. Occupants were required to leave the apartment at least 1 hr prior to initiation of background sampling (Stage 1) and were not allowed to return until after the completion of Stage 3. The HVAC system of each apartment was switched off 1 hr prior to Stage 1 and was left off for the entire experiment. All doors that connected the living room (vacuumed area) to other rooms in the apartment were closed before an experiment. All windows were closed for an experiment. Occupants did not cook on the day of and prior to an experiment.

Experiments involved vacuuming the carpeted living room areas of each apartment. This area ranged from 11 to 25 m^2, with a mean area of 18.3 m^2 and standard deviation of 5.0 m^2 over all 12 apartments.

Measurement Instrumentation

Particle mass concentrations were measured using the same laser photodetector aerosol monitor (8520 DustTrak; TSI Inc., Shoreview, Minn.) equipped with an inlet impactor system and fittings for either 10-μm or 2.5-μm cutoff. This device has a limit of detection and a resolution of 1 μg/m^3 when used with the same test aerosol used for calibration. The laser photodetector was calibrated to an Arizona Test Dust standard by the manufacturer immediately prior to the experimental program. It was zeroed before each experiment, and the sample airflow rate was checked and set to 1.7 L/min as per manufacturer recommendations. A 30-sec time-averaging period was employed for purposes of data logging. Due to the short duration of each experiment, it was not possible to compare the instrument measurements with gravimetric analysis of filter samples.

Experimental Variations

Experiments were grouped into six distinct sets of experimental conditions as listed in Table I. Experimental Groups 1 through 4 each involved VCA. Group 5 involved the use of VCB. Group 6 involved six experiments conducted in a single apartment in which no vacuum cleaner was used,

TABLE I. Variations in Experimental Conditions

Experimental Group	Vacuum Cleaner	Days Between Vacuum Events	Particle Cutoff (μm)	No. of Samples	Apartments Tested
1	VCA	10	10	8	1, 2, 2, 3, 4, 5, 7, 8
2	VCA	24–92	10	8	3, 4, 5, 6, 9, 10, 11, 12
3	VCA-off	10	10	6	1, 2, 3, 5, 7, 8
4	VCA	10	2.5	8	1, 1, 2, 4, 4, 5, 6, 6
5	VCB	10	10	10	1, 1, 2, 2, 3, 5, 6, 7, 8, 8
6	None	10	10	6	1, 1, 1, 1, 1, 1

except for 20 min an individual moved across the carpet simulating the foot-on-carpet contact that would occur for an actual vacuuming event. For all but Group 2, the standard time between vacuuming events was 10 days. For Group 2, the time between vacuuming events ranged from 24 to 92 days. For all but Group 4, the particle cutoff diameter was 10 μm. For Group 4, the laser photodetector was equipped with a 2.5-μm cutoff. For Group 3, the vacuum cleaner was switched off and was pushed and pulled across the carpet as if it was switched on. The last column of Table I indicates which apartments were used for each group.

Analysis of Data

Two different parameters were used to analyze and compare data within and between the experimental groupings listed in Table I. Parameter ΔC is the difference between the time-averaged particle mass concentration during and prior to (background) vacuuming. The parameter Z is the ratio of the peak 30-sec average particle mass concentration during vacuuming and the time-averaged particle mass concentration prior to vacuuming. These parameters (ΔC and Z) are shown in Eqs. 1 and 2, respectively.

$$\Delta C = \bar{C}_{vac} - \bar{C}_{back} \tag{1}$$

$$Z = \frac{C_{peak}}{\bar{C}_{back}} \tag{2}$$

where, $\bar{C}_{vac}$ = time-averaged particle mass concentration in room air while vacuuming (μg/m^3); $\bar{C}_{back}$ = time-averaged particle mass concentration in room air prior to vacuuming (μg/m^3); and C_{peak} = peak 30-sec average particle mass concentration in room air while vacuuming (μg/m^3).

For each experiment, a mean and a standard deviation for C were calculated for both the background and the vacuuming period. A two-tailed hypothesis test was completed on the equality of the mean concentrations for the background and vacuuming periods, with a significance level set at a value of $\alpha = 0.05$. The statistical comparison was done with a Behrens-Fisher approach, owing to the small sample sizes and nonequal variances of the data.[28] For each group of experiments described in Table I, the mean and standard deviations of ΔC and Z were determined to allow for statistical comparisons of different experimental conditions. The same hypothesis testing procedure described above was applied to ΔC and Z to compare means for each sampling condition. Six comparisons were conducted for ΔC and Z. The base case, defined as PM_{10}, Vacuum Cleaner A, and vacuuming with a 10-day interval from the previous vacuuming event, was compared with each of the other four groups of PM_{10} data. Additionally, the group of experiments with no vacuum were compared with the set of experiments with Vacuum Cleaner B as well as the experiments with VCA switched off.

RESULTS

Particle Mass Concentration Profiles

Particle mass concentration profiles were generated for each of the 46 experiments. Typical profiles for separate experiments involving PM_{10} and $PM_{2.5}$ measurements are shown in Figure 1. In most cases, a very small to imperceptible increase (above background) in $PM_{2.5}$ concentration was observed while

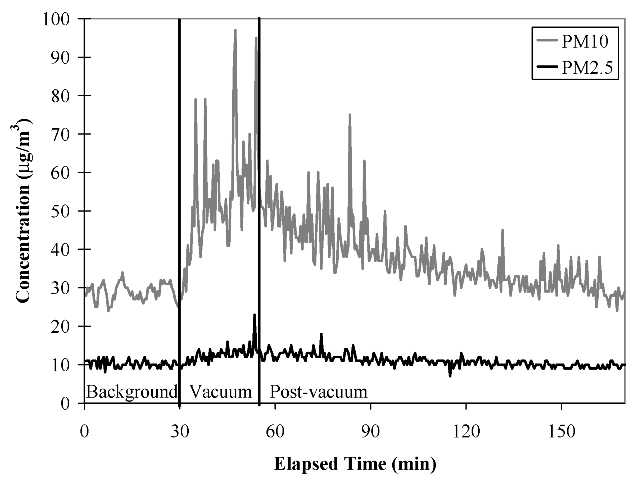

FIGURE 1. Example concentration profiles for two vacuuming experiments, each with a different measured particle size. Vacuuming began at 30 min and ended at 50 min in each case.

TABLE II. Results for Different Experimental Conditions

Experimental Group	Background Concentration, $\bar{C}_{vac}$ (μg/m^3)	Vacuuming Concentration, $\bar{C}_{vac}$ (μg/m^3)	Peak Concentration, C_{peak} (μg/m^3)
1	29 (26)	46 (23)	91 (39)
2	27 (13)	45 (16)	100 (31)
3	29 (17)	34 (15)	62 (23)
4	16 (7)	17 (8)	25 (13)
5	32 (37)	67 (44)	119 (68)
6	48 (9)	55 (10)	77 (8)

Note: Data are mean (SD).

vacuuming. In contrast, PM_{10} concentrations nearly always increased sharply when vacuuming commenced (at 30 min), and began to decline slowly when vacuuming was terminated (at min 50). Variations in particle mass concentration with time are likely attributable to mixing conditions in room air and proximity of the vacuum cleaner to the room-centered sampling device. Table II summarizes the concentration parameters for each experimental group.

Background Particle Mass Concentrations

The following statistics characterize the time-averaged background PM_{10} concentrations: Number of experiments = 38; range = 7–103 μg/m^3; mean = 32 μg/m^3; standard deviation = 22 μg/m^3; median = 28 μg/m^3. The following statistics characterize the time-averaged background $PM_{2.5}$ concentrations: Number of experiments = 8; range = 6–27 μg/m^3; mean = 16 μg/m^3; standard deviation = 7.5 μg/m^3; median = 15 μg/m^3.

Fine Particulate Matter ($PM_{2.5}$)

Fine particulate matter was measured during eight experiments in five different apartments. Vacuum Cleaner A (VCA) was used for each experiment. Each experiment was completed 10 days after the previous vacuuming event in each apartment. Values of ΔC ranged from a slight decrease to 3 μg/m^3. Five of the eight $PM_{2.5}$ tests showed a slight but statistically significant increase in particle mass concentrations, one showed a slight but significant decrease, and the remaining two experiments showed an insufficient change in particle concentrations to be able to reject the hypothesis that concentrations were the same before and during vacuuming. The mean and standard deviations of ΔC for $PM_{2.5}$were 1.1 and 1.1 μg/m^3, respectively, and the median was 1.0 μg/m^3.

The peak $PM_{2.5}$ concentration during vacuuming ranged from 9 to 52 μg/m^3, with mean and standard deviations of 25 and 13 μg/m^3, respectively. The median of the peak $PM_{2.5}$ mass concentrations was 24 μg/m^3. The peak ratio (Z) ranged from 1.17 to 2.30, with mean and standard deviations of 1.59 and 0.38, respectively. The median value of Z was 1.53. These values are lower than corresponding values for PM_{10} discussed below. Given the relatively small magnitude of the increases in $PM_{2.5}$ mass concentration observed during this study, the remainder of this article will focus on the effects of vacuuming on PM_{10} concentrations. However, it is worth noting that while $PM_{2.5}$ mass concentration increases were small, it is still conceivable that the increase in number concentration for particles less than 2.5 μm in diameter was substantial, since particles of this size contribute considerably less to airborne mass concentration than larger particles.[26,27] Furthermore, given the potentially serious health consequences associated with $PM_{2.5}$, care to protect sensitive individuals from peak $PM_{2.5}$ concentrations that result from vacuuming is warranted.

Coarse Particulate Matter (PM_{10})

The rise in particle levels relative to background was statistically significant for all 38 experiments involving PM_{10}, except for the following three experiments: one test with Vacuum Cleaner B (VCB) showed a slight but significant decrease in PM_{10} concentrations, and two tests (one with each vacuum cleaner) showed an insufficient rise in particle concentrations to be able to reject the hypothesis that concentrations were the same before and during vacuuming.

Values of ΔC for PM_{10} and each data grouping are shown in Figure 2. When each set of sampling conditions was analyzed separately, the ΔC values for each group all were found to be significantly greater than zero. Values of Z for PM_{10} and each data grouping are shown in Figure 3, and each of these sets of values was found to be statistically significantly greater than unity.

Comparison Between Cases and to Other Reported Work

For the ΔC parameter, there were three comparisons where the authors were able to reject the hypothesis of the equality of the means: (1) the base case set (VCA, PM_{10}, with 10 days between vacuuming events, Group 1) and the VCB experiments (Group 5); (2) the base case (Group 1) and the cases with no vacuum cleaner (Group 6); and (3) the experiments with VCA switched off (Group 3) and the set of data with no vacuum cleaner (Group 6). The comparison of cases for the Z parameter revealed only two comparisons where the authors were able to reject the hypothesis of the equality of means: (1) the base case (Group 1) and the experiments with no vacuum cleaner (Group 6); and (2) the experiments

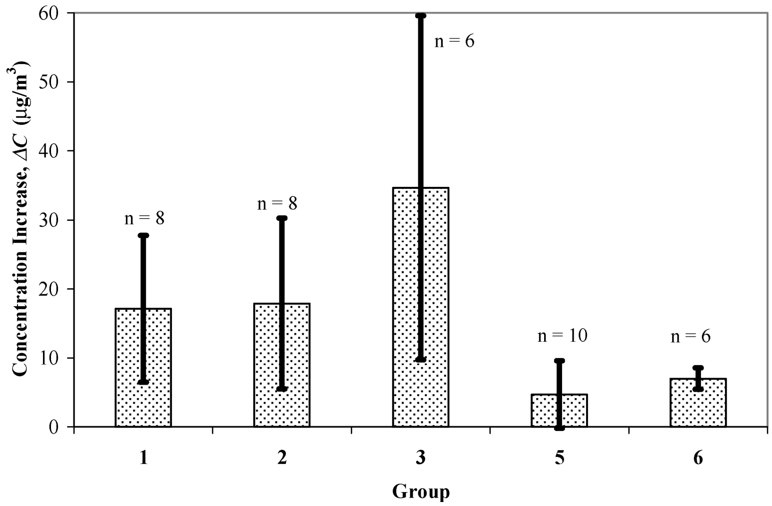

FIGURE 2. Concentration increase ΔC for experimental Groups 1–3 and 5–6 (PM_{10} experiments). Groups are described in Table I. Vertical bars represent ± 1 standard deviation. All results are statistically significant.

with VCA switched off (Group 3) and the set of data with no vacuum cleaner (Group 6). Although direct comparisons of the results discussed here with those reported by others are difficult because of differences in particle size and reported parameters, present study results are generally consistent with the concentration increases and peak concentrations reported by Thatcher and Layton,[25] Long et al.,[24] and Hildemann and Montoya.[23]

DISCUSSION

The results of this study indicate that the act of vacuuming carpet can be a significant short-term source of PM_{10}. Because floor dust contains a spectrum of allergens, vacuuming of indoor spaces logically increases the levels of indoor airborne allergens and the potential for allergy, asthma, and other outcomes. As such, it is important to avoid having those individuals with related allergies present during vacuuming events and for several hours thereafter. This can be accomplished by ensuring that vacuuming takes place during off hours in occupational and school settings and that those with allergies are not present during and for several hours after a vacuuming event in residential settings. In addition, control measures such as effective HVAC or portable filtration, properly designed and appropriate increased ventilation, or respiratory protective equipment should be considered. Additional research

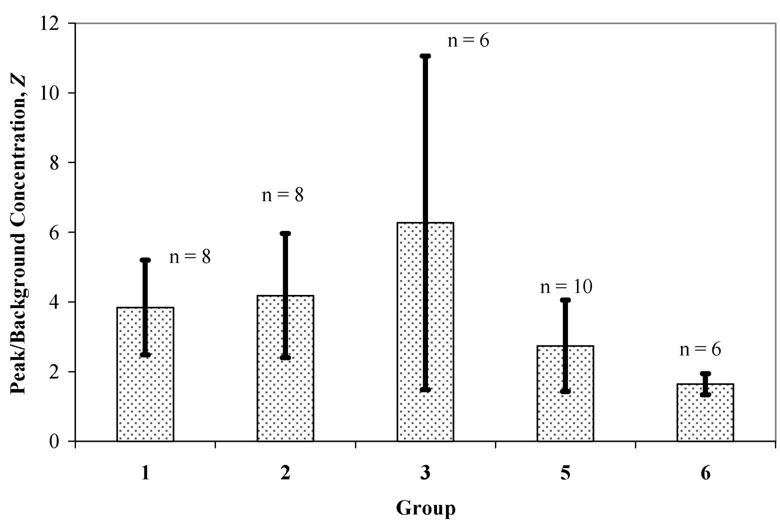

FIGURE 3. Peak concentration during vacuuming experiment normalized by average background concentration prior to vacuuming (parameter Z) for PM_{10} experiments. Groups are described in Table I. Vertical bars represent ± 1 standard deviation. All results are statistically significant.

is needed to identify the significance of particle exposures for those who are actually involved in vacuuming as an occupation.

Resuspension of particles by mechanical agitation, i.e., direct contact of vacuum cleaner components with flooring, may be an important contributor to PM_{10} emissions during vacuuming events. In this study, tests of one deactivated vacuum cleaner led to the highest mean values of the parameters ΔC and Z over all five test groups involving PM_{10}. However, particle resuspension is reduced when the vacuum cleaner is switched on, i.e., the suction from the vacuum cleaner appears to collect some of the particle mass that otherwise would have been emitted by mechanical agitation. It is not clear how much of the PM_{10} source strength that occurs during vacuuming is due to mechanically induced resuspension versus particle penetration through the vacuum collection system. A better understanding of these factors possibly would facilitate the design of vacuum cleaners that emit less particle mass; it remains an area for future research.

The results from Group 6 suggest that approximately half the mass emitted from VCA, on average, was caused by the action of walking on the carpet, although some of this mass may be recaptured as discussed above. There was no statistical difference in particle mass concentration increases between VCB (Group 5) and walking with no vacuum cleaner (Group 6).

The authors found a significant difference in ΔC for PM_{10} between VCA and VCB consistent with the findings of de Blay et al.[19] for *Fel d1* and Lioy et al.[26] for ultrafine and fine particle emissions from vacuum cleaner motors and suggesting the importance of differences between vacuum cleaners. The authors found no significant difference in either ΔC or Z between the tests done with 10 days between vacuuming events and events with a gap of 24 days. Although more frequent vacuuming may have an impact on hygiene, it does not seem to have an effect on resuspension of PM_{10}. This may be due to depletion of the reservoir of PM_{10} in the carpet by other resuspension sources, or it may be due to particles becoming more firmly attached to carpet fibers.

CONCLUSIONS

The major conclusions stemming from this study are listed below.

- Vacuuming significantly increases PM_{10} mass concentrations over background but has an insignificant impact on $PM_{2.5}$ mass concentrations. The authors found no dependence on PM_{10} mass concentrations on the time between vacuuming events.
- The design of a vacuum cleaner can affect particle emissions during vacuuming events. The authors found a statistically significant difference between the concentrations that resulted from the two vacuum cleaners tested in this study. This is consistent with other research in the literature and suggests that sensitive individuals should choose a vacuum cleaner that is independently verified to result in lower mass concentrations of PM_{10}.
- Sensitive individuals should not be present during or immediately after a vacuuming event.

The results presented herein should facilitate future research on human exposure to particulate during indoor occupational and residential cleaning activities.

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