Bio-walls and indoor houseplants: Facts and fictions

Microbiomes of the Built Environment: From Research to Application, Meeting #3

Arnold and Mabel Beckman Center
University of California, Irvine
October 17-18, 2016

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How well do potted plants or bio-walls clean the indoor air of organic gases?

1. Indoor air and organic gases
2. Plants and indoor air cleaning
3. Parameterizing air cleaning
4. Potted plants and air cleaning
5. Bio-walls and air cleaning
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1. Indoor air and organic gases

Why do we care about this potential?

- Americans spend ~90% of time indoors

- In buildings, we perform many activities, and fill them with furnishings, consumer products, and appliances

- This leads to emissions and high concentrations of many substances
  - Organic gases usually at higher concentrations than outdoors

- Buildings exchange air without the outdoors (e.g. ventilation)
  - Air exchange is the most common way to reduce indoor organic gases
  - However, conditioning ventilation (outdoor) air uses energy

- Health and productivity effects are related to building occupancy
1. Indoor air and organic gases

Classifying organic gases indoors

- Many health effects for building occupants:
  - **Acute**: Odors, irritation (eyes, mucus membranes), Sick Building Syndrome
  - **Chronic**: Carcinogens and mutagens
- Often meaningfully reactive (e.g. with ozone or hydroxyl radical)

Classifications of organic gases based on vapor pressure:

<table>
<thead>
<tr>
<th>Description</th>
<th>Abbreviation</th>
<th>Boiling Point Range (°C)</th>
<th>Example Compounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very volatile (gaseous) organic</td>
<td>VVOC</td>
<td>&lt;0 to 50-100</td>
<td>Propane, butane, methyl chloride</td>
</tr>
<tr>
<td>compounds</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volatile organic compounds</td>
<td>VOC</td>
<td>50-100 to 240-260</td>
<td>Formaldehyde, d-Limonene, toluene, acetone, ethanol (ethyl alcohol) 2-propanol</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(isopropyl alcohol), hexanal</td>
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<tr>
<td>Semi volatile organic compounds</td>
<td>SVOC</td>
<td>240-260 to 380-400</td>
<td>Pesticides (DDT, chlordane, plasticizers (phthalates), fire retardants (PCBs, PBB))</td>
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https://www.epa.gov/indoor-air-quality-iaq/technical-overview-volatile-organic-compounds
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2. Plants and indoor air cleaning

Some research proposes houseplants clean air

- Janet Craig
  *Dracaena deremensis*

- Ficus tree
  *Ficus benjamina*

http://tinyurl.com/zhgpep8

http://tinyurl.com/jsqdn68
2. Plants and indoor air cleaning

The Internet hype…

Refers to:
NASA Clean Air Study

- Initiated by NASA, with Associated Landscape Contractors of America (ALCA)
- Investigated air cleaning with plants for space purposes
- Wolverton et al. (1989)

http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930073077.pdf
2. Plants and indoor air cleaning

The Internet hype...

9 Air-Cleaning Houseplants That Are Almost Impossible to Kill

15 houseplants for improving indoor air quality

These are the best houseplants to improve indoor air quality, study finds

And... breathe.

Do Indoor Plants Really Clean the Air?
2. Plants and indoor air cleaning

Some research proposes houseplants clean air

- Chamber studies quantified removal of VOCs by potted plants:

  - Kim et al. (2010)
  - Orwell et al. (2006)

![Diagram showing chamber setup for chamber studies quantifying VOC removal by potted plants](Image)

![Graph showing toluene concentration over time for different doses and days](Image)

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Waring, M.S. • Bio-walls and indoor houseplants: Facts and fictions  
Slide 10
2. Plants and indoor air cleaning

Some research proposes houseplants clean air

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2. Plants and indoor air cleaning

Mechanism of organic gas removal

Removal by:

- above ground plant elements
- microbes in soil and around plant roots
- plant root or soil uptake

Cruz et al. (2014)
2. Plants and indoor air cleaning

Potted plants versus “bio-walls”

**Potted plants:** passive system

- Polluted air
- Nutrients water

- Environmental room

- Treated air

- Nutrients water

**Bio-wall:** active system

- Polluted air
- Nutrients water

- Botanical biotrickling filter system

1. Fan pulls air through plants/roots
2. VOCs partition from air to water
3. Microbes on plant roots remove VOCs

Figure from: Soreanu et al. (2013)
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3. Parameterizing air cleaning

Clean air delivery rate (CADR)

- Clean air delivery rate (CADR) parameterizes air cleaner potential
  - \( \text{CADR} = \text{volumetric flow rate of clean air (m}^3/\text{h)} \)

**CADR** is product of air cleaner flow rate \( (Q_{ac}, \text{m}^3/\text{h}) \) and removal efficiency \( (\eta_{ac}) \)

\[
\text{CADR} = Q_{ac} \eta_{ac}
\]

First order loss \( (L_{ac}, \text{h}^{-1}) \) is CADR normalized by volume \( (V, \text{m}^3) \), which can be used in differential equations for concentrations, \( C \):

\[
\frac{dC}{dt} = \lambda C_{out} + \frac{E}{V} - \left( \lambda + \frac{\text{CADR}}{V} \right) C
\]
3. Parameterizing air cleaning

Clean air delivery rate (CADR)

- Clean air delivery rate (CADR) parameterizes air cleaner potential
  - **CADR** = volumetric flow rate of clean air (m³/h)

For effective cleaning, the air cleaner loss must be $O$(air exchange rate, $\lambda$)

- $\lambda \gg \frac{\text{CADR}}{V}$: Little impact
- $\lambda \ll \frac{\text{CADR}}{V}$: High impact
- $\lambda \cong \frac{\text{CADR}}{V}$: Equal impact to air exchange

Air exchange rate, $\lambda$, is volume normalized flow of outdoor air through a space
3. Parameterizing air cleaning

Air cleaner effectiveness ($\Gamma$)

- $\Gamma$ parameterizes fraction of pollutant removed by air cleaner
  - $\Gamma = 1 - \left(\text{concentration with air cleaner} / \text{concentration without air cleaner}\right)$

WITH air cleaner steady state $C$:

$$C = \frac{\lambda C_{\text{out}} + E/V}{\lambda + \frac{\text{CADR}}{V}}$$

Air cleaner effectiveness varies with volume ($V$, m$^3$) and air exchange rate ($\lambda$, h$^{-1}$)

$$\Gamma = 1 - \frac{\lambda}{\lambda + \frac{\text{CADR}}{V}}$$
3. Parameterizing air cleaning

Air cleaner effectiveness ($\Gamma$): Demonstration

- For an air cleaner with a CADR = 50 m$^3$/h

Within a $V = 50$ m$^3$ office, with an air exchange rate ($\lambda$) of:

- $\lambda = 0.2$ h$^{-1}$  \hspace{1cm} $\Gamma = 0.83$
- $\lambda = 1$ h$^{-1}$  \hspace{1cm} $\Gamma = 0.50$
- $\lambda = 4$ h$^{-1}$  \hspace{1cm} $\Gamma = 0.20$

where $\Gamma = 1 - \frac{\lambda}{\lambda + \frac{\text{CADR}}{V}}$
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Figure from: Soreanu et al. (2013)
4. Potted plants and air cleaning

Can potted plants effectively clean the air?

- Removal in chamber studies converted to CADR:

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Can potted plants effectively clean the air?

• Removal in chamber studies converted to CADR:

Using chamber volume, $V$, metrics can be converted to $\text{CADR} = L_{ac} V$ assuming concentration changes are first order owing to air cleaner loss, $L_{ac}$, over a time horizon, $t$:

$C_2 = C_1 \cdot \exp (-L_{ac} t)$

$C_2 = C_1 \cdot \exp \left( -\frac{\text{CADR}}{V} t \right)$

$\text{CADR} = -\ln \left( \frac{C_2}{C_1} \right) \frac{V}{t}$
## 4. Potted plants and air cleaning

Can potted plants effectively clean the air?

- Removal in chamber studies converted to **CADR**:

  - Benzene (n=16)
  - Formaldehyde (n=11)
  - Toluene (n=3)
  - Trichloroethylene (n=5)
  - m-Xylene (n=3)
  - n-Hexane (n=3)

  **Outliers** (n=2 of 11) 0.32 m³/h/plant

### References:

Aydogan & Montoya (2011); Irga et al. (2013); Kim et al. (2008); Orwell et al. (2004); Orwell et al. (2006); Wolverton et al. (1989); Wood et al. (2002)
4. Potted plants and air cleaning

Can potted plants effectively clean the air?

- **CADR** determines no. plants required for effectiveness, $\Gamma$, at volume, $V$:
  - No. plants/m² needed for $\Gamma = 0.5$ at air exchanges, $\lambda = 0.2, 1, \text{ and } 4 \text{ h}^{-1}$

Required **CADR** for given effectiveness:

$$\text{CADR}_{\text{req}} = V \left( \frac{\lambda}{1 - \Gamma} - \lambda \right)$$

Required plants for required **CADR**:

$$\text{No. plants} = \frac{\text{CADR}_{\text{req}}}{\text{CADR}} = \frac{\text{m}^3/\text{h}}{\text{m}^3/\text{h/plant}}$$

Number of plants required is infeasible to clean air

- **y-axis** on log-scale
4. Potted plants and air cleaning

So even this set-up would clean the air negligibly…

http://tinyurl.com/h4kfz5c
4. Potted plants and air cleaning

What do some field studies show?

- Associated Landscape Contractors of America (ALCA) and Healthy Buildings International (HBI, 1992)
  - Method: 2 identical offices, varying which one had plants; no AER
  - Results: No reduction in pollutants with plants

- Dingle et al. (2001)
  - Method: 3 offices, add 5 plants every 2 days to 20 plants (2.5/m²); no AER
  - Results: No change except at 20 plants (11%)

- Wood et al. (2006)
  - Method: Three buildings, ~9 offices each; varied 0, 3, or 6 plants; no AER; VOCs measured only 5 minutes/week (!)
  - Results: Little change except with 6 plants

Girman et al. (2009)

No conclusions can be drawn without air exchange rate (AER)
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Figure from: Soreanu et al. (2013)
5. Bio-walls and air cleaning

Schematic of bio-wall and Drexel bio-wall:

Bio-wall schematic

Figure from: Soreanu et al. (2013)

Drexel Bio-wall

http://tinyurl.com/zju4bsd
5. Bio-walls and air cleaning

Can bio-walls effectively clean the air?

- Bio-wall removal can also be converted to **CADR** \((m^3/h/m^2)\):
  - Scant in-situ data, this discussion will use work from Darlington et al. (2001)

\[
y = -0.21 \ln(x) - 0.21 \\
R^2 = 0.64
\]

**CADR** is product of air cleaner flow rate flux \(Q_{\text{bio}}, m^3/h/m^2\) and its removal efficiency \(\eta_{\text{bio}}\)

\[
\text{CADR} = Q_{\text{bio}} \eta_{\text{bio}}
\]

Normalized by bio-wall area

Figure from: Soreanu et al. (2013)
5. Bio-walls and air cleaning

Can bio-walls effectively clean the air?

- Bio-wall removal can also be converted to CADR ($m^3/h/m^2$):
  - Scant in-situ data, this discussion will use work from Darlington et al. (2001)

<table>
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<tr>
<th>Percentiles</th>
<th>CADR ($m^3/h/m^2$)</th>
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<tbody>
<tr>
<td>5th</td>
<td>24.5</td>
</tr>
<tr>
<td>10th</td>
<td>36.0</td>
</tr>
<tr>
<td>25th</td>
<td>52.2</td>
</tr>
<tr>
<td>50th</td>
<td>75.6</td>
</tr>
<tr>
<td>75th</td>
<td>94.5</td>
</tr>
<tr>
<td>90th</td>
<td>140</td>
</tr>
<tr>
<td>95th</td>
<td>155</td>
</tr>
</tbody>
</table>
5. Bio-walls and air cleaning

Can bio-walls effectively clean the air?

- **CADR** determines the bio-wall area for effectiveness, $\Gamma$, at volume, $V$
  - Bio-wall area (m$^2$) needed for $\Gamma = 0.5$, at air exchange of $\lambda = 0.2$, 1, and 4 h$^{-1}$

Required **CADR** for given effectiveness:

$$\text{CADR}_{\text{req}} = V \left( \frac{\lambda}{1 - \Gamma} - \lambda \right)$$

Required area for required **CADR**:

$$\text{Biowall area} = \frac{\text{CADR}_{\text{req}}}{\text{CADR}} \left[=\right] \frac{\text{m}^3/\text{h}}{\text{m}^3/\text{h/ m}^2}$$

Bio-wall areas are feasible to clean air
5. Bio-walls and air cleaning

Potential issues with bio-walls

• Need for rigorous field studies that verify real impacts

• Plants emit VOCs, some of which react (e.g.) with ozone ($O_3$)
  • SOA (secondary organic aerosol) from $O_3$ + plants (Joutsensaari et al., 2005)

• Bio-wall utilizes water for plants and as part of operational mechanism
  • Hydrophobic VOCs are likely less removed
  • Humidity may be elevated as air passes through bio-wall water
  • Bio-wall water could harbor pathogens (e.g. Legionella)

• Spores are likely emitted from bio-wall
  • Seen in a room-scale lab test (Darlington et al., 2000)

• Bio-walls may be more expensive than pure ventilation
  • Our preliminary modeling implies this is often the case
Conclusions

How well do potted plants or bio-walls clean the air?

Potted plant conclusions
• Potted plants must be at unrealistic densities to clean air effectively
• If more research is conducted, **rigorous field work** must verify impact

Bio-wall conclusions
• Bio-walls are (likely) capable of cleaning air effectively
• Future research should focus on:
  • Rigorous field work that verifies real indoor air impacts
  • Potential negative impacts of bio-walls indoors
  • Cost-benefit analysis of this technology
References

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Thank You