Evolving Frameworks Towards Identifying Challenges and Opportunities of Indoor Vegetation Systems

Christina Ciardullo, AIA*
Member ASHRAE

Andreas Theodoridis, PhD*

Phoebe Mankiewicz
Student Member ASHRAE

Mohamed Aly Etman, PhD

Naomi Keena, PhD

Anna Dyson

ABSTRACT

Our planet is rapidly urbanizing, leading to significant biodiversity loss. In architecture and urban planning, public and private developers are scaling up the integration of vegetation into built environments through applications such as green roofs, urban farms, and bioremediation systems, in some cases designed as novel additions to mechanical systems. In indoor environments, investigations into active biofilters for improving Indoor Air Quality (IAQ) have been investigated for several decades. As much of this research remains in disparate fields of inquiry and examines specific aspects of the indoor ecosystem, there are still many gaps in the knowledge, leaving building design professionals without comprehensive or standard frameworks to make actionable decisions on their anticipated performance. To establish more systematic frameworks for evaluating building-integrated bioremediation and vegetation systems, the shift towards more comprehensive Indoor Environmental Quality (IEQ) metrics suggests a broader, more inclusive range of evaluative criteria at scale, towards multivalent value propositions. In addition to airborne pollutant removal rates, the impact of vegetation systems on a range of factors such as acoustic and thermal performance, allows for a more pragmatic and comprehensive assessment of value. Additional methods of evaluation, including: (1) the Life Cycle Analyses (LCA) of energy, water and material use; (2) the potential health benefits of a more diverse microbiome; (3) biophilic effects, and; (3) stakeholder frameworks (such as ecosystem services, etc) and future value systems that could offer more comprehensive environmental performance metrics through which to evaluate systems. Evolving frameworks capable of integrating disparate metrics are necessary to: (1) direct fundamental research towards more applicable experimental reporting values; and (2) provide accessible frameworks for decision makers when considering indoor vegetation systems.

INTRODUCTION

Motivations: The Need for Metrics in the Context of Increased Demand for Building Integrated Vegetation

The building industry is experiencing increased social and market driven expectations [1] and in some cases legislative incentives or mandates [2], for *Building-Integrated Vegetation* (BIV) systems: the growing of plants on the exterior and interior surfaces of buildings in applications such as green roofs, green facades, and indoor green walls. Perhaps it is in the spirit of growing environmental consciousness, alongside emerging research, that more verifyiable assessment frameworks for the performance of these systems needs to be established. As interest in indoor BIV expands, architects and other decision makers within the built environment require methods of evaluating systems to make actionable decisions on their implementation in building projects. If not properly characterized, there is a risk to introduce unfounded systems into buildings, or alternatively handicap what could be potentially effective solutions. It is in this context of the pressing need for

*equal contribution first author
Christina Ciardullo is a licensed Architect in New York and Ph.D. student at the Center for Ecosystems and Architecture (CEA), Yale University, New Haven, CT**. Dr. Andreas Theodoridis** is a licensed Architect-Engineer in Greece and received his Ph.D. at the Center for Architecture, Science and Ecology, RPI, Troy, NY. **Phoebe Mankiewicz** is a senior Ph.D. student at CEA, Yale University, New Haven, CT. **Dr. Mohamed Aly Etman** is a Research Scientist and Lecturer at the CEA, Yale University, New Haven, CT. **Dr. Naomi Keena** is an architect, interdisciplinary researcher, and assistant professor at McGill University School of Architecture. **Anna Dyson is** a dually appointed Hines Professor of Sustainable Architectural Design at the Yale School of Architecture and School of Environment, Director of CEA, Yale University, New Haven, CT, and directing this area of research.

metrics to evaluate indoor BIV, that we are investigating the implications of moving from Indoor Air Quality (IAQ) to Indoor Environmental Quality (IEQ) performance assessments for indoor plant-based systems. While this remains an emerging field, we are summarizing preliminary evidence in distinct fields of IEQ and highlighting the need to reframe those assessments through the lens of ecosystemic interactions, not only across IEQ but with additional metrics from the standpoint of the Built Environment Process (BEP).

On the Challenges of Maintaining Current Mechanical Building Practices

With an increase in urbanization [3], a growing majority of people spend 87% of their time inside buildings [4], relying on them to provide comfortable and healthy indoor environments. Prior to the modern era, buildings were not as dependent on mechanical and electrical systems as they are today. Developments in building air handling systems and materials throughout the modern era increasingly tended towards centrally controlled mechanical strategies and envelope enclosures that favor the performance criteria of predictable reliability and homogeneous separation from the fluctuations of ambient weather conditions. Conventional mechanical Heating, Ventilation, and Air Conditioning (HVAC) systems have become prevalent across the global commercial building industry for regulating thermal comfort and air quality.

However, the increasing dependence and reliance on mechanical systems has not come without cost. In the United States in 2015, building use accounts for 40% of the nation's total energy use with mechanical HVAC representing 16% of that energy demand [5]. Following the energy crisis of the 1970s, ASHRAE published *Energy Conservation in New Building Design 90,* the first standard reflecting increasing concerns on energy use [6]. Currently, energy use analysis and energy commissioning is an integral part of evaluating building and systems design. While there may be some benefits in separating energy performance from other criteria [7], from the standpoint of whole building delivery, it is highly interdependent with IEQ performance. In addition, the unwanted byproducts of these HVAC services come in a multitude of forms, from excessively produced waste heat that alters the microclimate of the building's surroundings, to additional air pollution that is exhausted by the running cycles of the equipment, to excess noise, inadequate mass balance of oxygen to carbon dioxide (CO_2), unsatisfactory humidity levels in heating degree months [8-10]. Furthermore, the use of ventilation as a de-facto measurement of indoor air quality becomes problematic when outdoor air quality is compromised, particularly in urban environments [11, 12]. Moreover, 80% of building occupants remain dissatisfied with indoor comfort [13].

The increased dependency on mechanical and physio-chemical methods of controlling our interior environments has occurred alongside the separation of other living systems and processes from the built environment. More recently, the health and well-being impacts of that separation has become increasingly scrutinized. Emerging data suggests that a multitude of varaibles including the filtration action of conventional HVAC systems [14], ventilation regimes [14], and biogeography [15] have led to reductions in diversity of indoor microbial communities. This reduction in diversity in urban airstreams has been subsequently correlated with reductions to human-associated microbial communities and health impacts such as asthma rates and pathogen prevalence [16, 17]. It is broadly understood that these relationships are coreleational, however causal evidence is evolving for the converse relationships: design interventions have been related to increases in environmental and human associated microbial diversity, with measurable benefits to immune health in children [18]. These concerns at the micro level also manifest in health and well being metrics at the macro level, with increased investigation into biophilia, or the psychological benefits of contact with nature, and conversely with the chronic stress and other indicators of impoverished well being in the absence of connection to the natural world [19-21]. These health and wellbeing concerns, alongside energy conservation policies, have undermined the certainties and unchallenged hegemony of conventional air handling approaches and have opened the door for investigation into alternative or supplemental bio-mechanical hybrid strategies, such as BIV.

Multivalent Potentials for Bio-mechanical Alternatives Across Individual IEQ Categories

In response to some of the aforementioned limitations of mechanical systems, vegetation-based installations have emerged as potential alternative strategies towards benefiting multiple IEQ factors. Biomechanical-hybrid systems for the production of various performances inside buildings have been in development within the aerospace industry since the early 1950s. Studies have included oxygen production for space habitats through the use of algae based systems [22, 23], and indoor plant-based systems in development for the indoor production of agriculture, the production of energy [24], and even the indoor treatment of grey and black water [25]. Systems which are meant to regulate the interior environment in terms of an IEQ framework have also emerged, perhaps most notably in the area of indoor air bioremediation for the control of IAQ. Investigations into the use of plant-based systems towards the removal of volatile organic compounds (VOCs) from the 1960s to the 2000s, which began in the context of highly sealed chamber studies for aerospace environments at NASA [19, 26-28], has arguably brought research in indoor air biofiltration into scholarly exchange for the past four decades.

Partially because of the origins of this research at NASA, historically the relationship to VOCs remediation has been a priority of indoor BIV. Research over the past four decades suggests that indoor BIV may provide opportunities to metabolize or sesquester certain pollutants through interaction with leaf structures and microbes in the root rhizosphere[19, 28-30]. While it has been demonstrated that microbes can metabolize VOCs in other contexts [31, 32], the behavior of microbial communities within plant systems has not been adequately characterized with respect to the relationship between airborne VOCs and the rate required to have an impact on larger volumes of indoor spaces. In addition, there are multiple mechanisms through which VOCs might be removed from air streams that do not involve metabolizing such pollutants including water flow transport and/or the sequestration within plant growing media [29, 33].

As interest in these systems has increased, emerging research in indoor BIV systems shows promise beyond VOC remediation. Though the performance factors which contribute to subjective values of human comfort continue to be defined, the four currently accepted principle categories include: (1) acoustic comfort; (2) thermal comfort; (3) indoor air quality; (4) and visual comfort [34]. In additional metrics of IAQ, the ability for the leaf area of plants to photosynthesize opens up investigation into the degree to which they may participate in CO_2 mass balance in indoor spaces [35-38]. Many other critical design factors impact the determination of CO_2 mass balance, such as plant species, circadian rhythms, microbial respiration, water availability and light intensity, among other factors [38]. Much of this research exists independently from the domain of bioremediation which may contribute to challenges in evaluating these systems with comprehensive information.

Beyond IAQ, others have considered the potential for cooling and increased humidity from evapotranspiration [39, 40] or to impacts on acoustic performance[41-45]. In terms of visual comfort, human comfort levels are often contrasted with the higher lighting levels required for photosynthesis [46]. In response to health and wellbeing concerns, emerging research suggests the potential for the introduction of plant-based microbial communities might have implications in supporting a diverse microbiome that could bolster immunity [16-18, 47] as well as potential biophilic benefits [19]. The potential of plant-based systems to ecosystemically address some of the limitations of current physicochemical mechanical systems, or to partially offset mechanical requirements and therefore energetic demands of heating, cooling, and ventilation is currently under investigation here.

CRITICAL RESPONSE TO BIO-MECHANICAL ALTERNATIVES

Despite ever increasing market demand and social expectations for both indoor and outdoor BIV, and increasing evidence to support the connection between plant-based systems with multiple values in the BEP, there remain many criticisms and questions of the demonstrated performance of these systems. To date, associations such as ASHRAE remain unforthcoming on the subject citing in a recent position paper “The air-cleaning effects of plants and new air-cleaning technologies, for which there is very limited scientific and technical literature, are not considered” [12].

Efficiency versus Effectiveness. The United States Environmental Protection Agency (EPA), in a 2018 IAQ technical summary, exemplifies a related evaluation scenario for residential air cleaners, with a range of evaluation methods that span from *efficiency* to *effectiveness* [48]. According to the EPA, *efficiency* is defined as a fractional measurement of a device or component's ability to reduce pollutant concentration in a single air pass through the equipment. The unit more often used to state this value is Minimum Efficiency Reporting Value (MERV) and is recorded under lab-controlled conditions. In contrast, the *effectiveness* of a device or system is a more inclusive measurement of its compounded ability to remove pollutants from spaces in real-world scenarios. In this case, *effectiveness* is mostly associated with the value Clean Air Delivery Rate (CADR). Criticisms of chamber experiments utilizing potted plants have asserted that the experimental conditions demonstrating *efficiency* are not representative of occupied building or zone-scale pollutant concentrations. For instance, a 1992 comment from the EPA concluded that scaling up chamber results to typical residential volumes resulted in unreasonable numbers of plants [49, 50] and suggest that the appropriate assessment incldue the mass of pollutants removed per hour per plant as a measure of *effectiveness*. More recently, efforts have been made to translate previous experimental results into CADR, thereby normalizing removal efficiencies by relevant volumes [51]. Thus, the critical response to early experimentation appears to largely have been a problem of mismatched evaluative frameworks and deployment context. Future frameworks need to properly characterize the discrepancies between lab conditions and occupied buildings.

Typological Differences. Contributing to the confounding factors in understanding these systems is the fact that there are critical design differences between building integrated green wall systems that range from potted plants in soil which could be considered *passive* systems, to *active* hydro-aeroponic systems that rely on blowing air through the root rhizosphere, either as stand-alone systems, or integrated into building HVAC. These passive and active systems are often conflated in conclusions regarding the potential efficacy of plant based systems to remediate indoor air [51]. For example, ineffective removal rates of potted plants are conflated with systems actively draw air through root systems which "may create a more effective means of VOC removal because of their size, exposed rhizosphere, and controlled and continuous airflow…with the potential to make worthy contributions to indoor VOC removal" [51]. While some question the energy requirements of active systems, analysis is required to identify to what extent these systems impact the heating and cooling loads by potentially lowering ventilation rates specifically according to type, as the context of daylighting, spatialization and systems integration would lead to substantial variability in energy demands [52-55]. Additionally significant is growing substrate which range from variations of felt based systems to modular tray systems [56] filled with multiple varieties of growing media which have significant impact on water retention, wet/dry cycles, biological activity, and airflow rates [38, 57]. Just as performance evaluation is "design agnostic," critical assessments cannot be applied to BIV as a whole without accounting for significant typological differences and specific design characteristics.

Multi-stakeholder Costs and Disservices. In addition, design considerations require performance evaluation that addresses additional potential disservices from the perspective of multiple built environment stakeholders. One major concern includes the potential of mold spores from overly damp or humid spaces [58]. Surfaces with growing substrates which can cause stagnation in air or water flow may be susceptible to growth of unwanted fungi, however these effects are design-dependent and may be mitigated by the choice of aforementioned growing substrate, consistent airflow, or horticultural management [59]. Indeed, systematic studies have showed no increased presence of pathogenic mold in the case of systems with consistent airflow [60]. Plants have also been cited as a potential source of VOCs [49], though there remain questions as to which species of VOCs may have negative human health impacts. Others cite concerns that root-based microbial communities may complicate CO_2 mass balance [61]. The list of concerns goes on, including the extent to which any particular system may cause structural damage due to root incursion, introduce unwanted pests, odours and allergies, or require excessive energy, water, or maintenance resources [20]. These are significant considerations critical to decision makers, but are only manifest when expanding the necessary performance criteria beyond single domain concerns.

Systemic Limitations of Existing Frameworks for Analyzing Multivalent Systems within the Current Mechanical Physio-Chemical Air-Handling Paradigm

As the questions on performance continue to be investigated, there remains a gap between the potential compound impacts of these designed living systems in the literature, and the realities of the context in which these systems operate within the built environment, including trade-offs with current mechanical physio-chemical methods. It may be that this gap in knowledge is perpetuated by the lack of standard metrics of evaluation which reflect the relevant contextual applications of complex indoor volumes which are not constrained by domain specific problems. Currently, indoor plant systems research, much like individual categories of IEQ, remain focused on one performance metric at a time. In the case of plant-based air remediating systems, the focus on experimental reporting in percent removal rate mirroring MERV rather than CADR has stagnated some of this research [51]. Researchers in this arena seeks to justify the potential of these systems by addressing the projected reduction in energy costs of ventilation [27, 57] or by comparing these systems with physiochemical filters such as adsorption filters, photocatalytic oxidation cleaners, and ozone generators [62]. Others have responded in kind with comparisons to the metrics used to analyze mechanical systems, namely the efficiencies of mechanical ventilation [51, 63] rather than reframing the potentials of these systems in the broader context.

This approach is understandable as a majority of IAQ evaluation metrics use ventilation as a benchmark in itself, an indicator which is one step removed from baseline biophysical measures of IAQ which specify levels of pollutant concentrations [7, 64]. Such assumptions become problematic when energy or outdoor air quality is of concern [12]. The prior studies set up an "all or nothing" scenario for comparing plant-based performance to conventional HVAC methods. However, future system designers require the scale at which plants may significantly bolster IAQ delivery methods and impact other dimensions of health, without needing to entirely replace existing approaches,. For example, one study estimated the area of one particular design of green wall requiring $5m^2$ of area to support the respiration of one occupant, but a smaller area of $1m^2$ was able to create reductions of CO_2 which would have an effect on human health [36]. These questions of appropriate or valid metrics or benchmarks highlight the concern that the evaluation system used to understand IAQ is predicated on existing mechanical paradigms, even at the expense of other critical requirements in the BEP.

Moving from IAQ to IEQ: Integrated Ecosystemic Metrics

If indeed plant-based systems were evaluated solely on the ability to compete with ventilation, the industry may miss an opportunity to capitalize on potentially synthetic performance in multiple aspects of IEQ. The industry already recognizes the necessity to move from evaluating isolated performances towards ecosystemic processes. ASHRAE Guideline 10: *Interactions Affecting the Achievement of Acceptable Indoor Environments,* first published in 2011, highlighted the problematic effects of compartmentalizing indoor performance categories with fundamental interactive relationships, including the potential to design for some performance factors at the expense of others, such as the imapact of HVAC on acoustic comfort or the impact of lighting design on thermal loads [65]. Currently, separate building codes and guidelines are considered as problem instances to be solved largley in isolation sacrificing the potential for holistic environmental and sociological solutions [66, 67]. IEQ alongside other interdependent factors in the BEP need to be negotiated throughout the design and construction administration phases [68, 69]. Prior to the intense mechanization of buildings, the architect acted as a single domain expert managing the complex building process. This chronicled legacy continues with the architect still at the center of the BEP but arguably more as a coordinating entity negotiating the competing pressures from constituent domain experts, responsible for addressing the requirements for their respective system areas. Architecture, Engineering and Construction (AEC) design professionals who operate at this nexus of information need more viable frameworks to evaluate multiple agendas. Current methods do not provide sufficient means to model, visualize or understand the impact of one decision on all of the other key components of the design enterprise [66, 67]. As BIV represents an area which can have impact in many domain areas it necessitates frameworks capable of incorporating the inclusion and interaction between multiple data steams potentially addressed by increased integration of building information modeling (BIM) and emerging computational techniques including machine learning [70].

Integrated IEQ Metrics may offer a More Applicable Framework to Evaluate BIV

Attempting to use the evaluative metrics derived from the current mechanical paradigm to value and quantify the potential multi-valent opportunities and challenges of BIV may not be viable for these systems due to the ecosystemic complexity of interdependent performance behaviors inherent to living systems. We are currently at an inflection point within the building industry, as the pressure to use potentially renewable biological or biomechanical processes is met with evaluation methods that are potentially antithetical to their implementation. In the interests of moving from evaluating the efficiency of isolated performances to measures of ecosystemic effectiveness for complex interior ecosystems, there is an opportunity to revisit both the value proposition and necessary data required to design with living systems. With plant-based research operating on mechanical terms, and arguments both for and against being assessed through the lens of existing frameworks, the interdependence between research reporting and practical applications assessment is clear. Decision makers in the built environment adhere in large part to guidelines, standards, and regulations to define the design of the mechanical and building systems and components of a project, relying on regulatory bodies' frequent appraisal of current scientific evidence. In practice, there remains a gap between scientific literature, assessment frameworks, and design in the BEP [71]. On the one hand, research that relies on the metrics described by current regulatory bodies may more easily integrate new knowledge into architectural practice. At the same time, current metrics are largely prescriptive requirements based on current best practices and might not necessarily support novel approaches [6, 72, 73]. If we develop evaluation frameworks that are congruent with ecosystemic behaviors representative of the scale of the built environment, then living systems may be able to show value that can be quantified and qualified in ways that can be accessible to decision makers.

EMERGING APPROACHES

Approaches to Synthesizing Relationships between Plant System Characteristics and Measures of IEQ

In order to begin to evaluate the implications of different plant characteristics on various performance aspects across IEQ, we are investigating a methodological approach to creating an integrated ontological framework, or a set of categories and definitions which can be commonly understood and applied across disciplines [74]. Towards this end, we are distilling relevant biophysical metrics and plant system characteristics on the one hand with different indicators, objectives, and values on the other. Relevant IEQ biophysical metrics (ie. temperature, humidity, ppm, CO_2, etc.), plant system characteristics (ie. species, leaf area, planting area, growing media type, etc), and built environment characteristics (ie, room or zone volume, occupancy, etc), extracted from the individual categories in the literature, are subsequently layered to reflect multiple performance interactions.

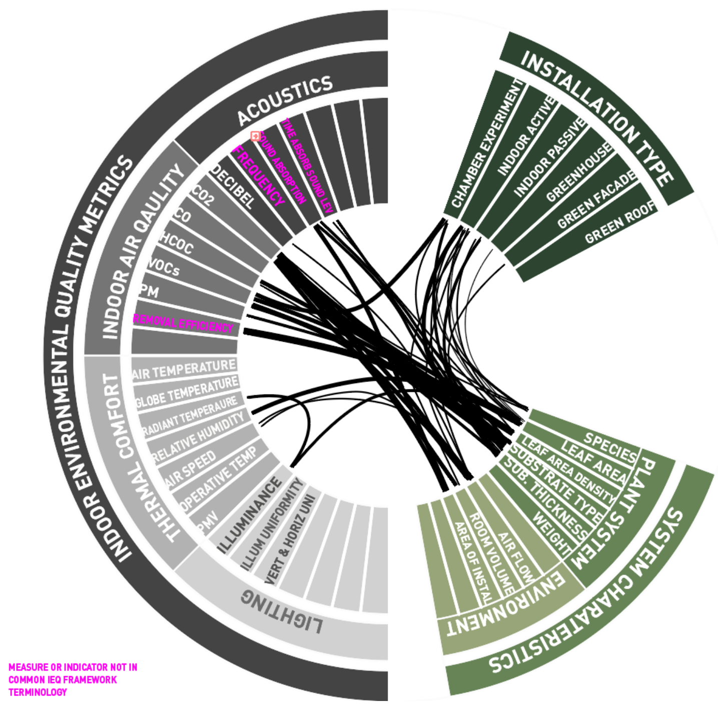
Plants and Indoor Air Quality. ***VOCs and HCHO*** While several mechanisms of pollutant removal have been investigated, emerging data suggests that the diverse microbial community within the root zone may have the best potential to remediate certain air pollutants through their metabolic activities, although these claims remain controversial and the mechanisms are still poorly characterized [26, 28, 57, 75-78]. Because of this, the design of growth media to accommodate a diverse microbial community may be a critical design factor in terms of air quality performance [38].

CO_2 As photosynthesis takes place in the leaves, leaf area or leaf area index (a measure of leaf area per ground surface) may be considered the primary driver within systems which prioritize CO_2 exchange, however it is not the only driver. Photosynthetic rates are dependent on species, lighting intensity, watering regime, and other factors [79]. However, as CO_2 exchange and photosynthesis are measured in number units (umol/m^2/s) [80], emerging research must account for the impact that interior volumes of typical interior spaces have on resultant concentration calculations.

Plants and Thermal Comfort. The potential for indoor plants to safely introduce passive humidification in the heating degree periods may be a great benefit of these systems. Controlling for unwanted excess humidity during hot-humid periods presents a parallel challenge. One study found that the increase in relative humidity due to the presence of plants was more significant when ventilation was not present, that maintaining comfort levels was viable, but key plant characteristics for increased evapotranspiration would need to include coverage density and leaf area [55]. Other studies reveal that the presence of a substantial number of plants improved occupant perception of thermal comfort, which, if not a biophysical measure of thermal comfort, is a metric in its own right allowing buildings to reduce energy consumption by altering building temperature set points [39, 81, 82].

Plants and Acoustic Comfort. For those studies using either laboratory scale experiments using impedance tubes or reverberation chambers, or in-situ green walls or potted plants, where sources of indoor noise include HVAC systems, significant sound absorption was reported for several plant systems [44, 83]. Plant species morphology is found to have some contribution to sound attenuation; however, findings were most significantly correlated with the sound absorbing properties of the planting substrate, noting porosity and thickness as relevant design characteristics [41-45].

Plants and Visual Comfort. Much of the literature concerning plants and lighting in indoor environments focuses on the relationship between luminance levels, carbon dioxide levels, and photosynthesis. At first glance, the lighting levels required for optimum photosynthesis, typically measured in Photosynthetically Active Radition (PAR) as opposed to typical built environment units of lumens, lux, or footcandles, would be far higher than lighting levels suitable for human comfort, particularly in plant systems that are substantially supplemented with artificial lighting [46, 84]. If plant systems rely on natural light, then architectural approaches need to be investigated for the appropriate percentage of building envelope covering and other related space occupation concerns, with respect to unwanted solar heat gain and glare. There is also significant potential for plant systems to modulate and mitigate the latter concerns.



Figue 1. Literature relevant to the impact of BIV on indoor environmental quality performance was evaluated. Plant system characteristics (ie. leaf area, substrate, etc), relevant environmental characteristics (ie. room volume), and installation type, was mapped against biophysical measures in all four areas of IEQ in order to visualize the intereactive and interdependent effects of BIV to design characteristics. Thickness of line indiciates the number of references.

Towards Synthetic Integration of Multiple IEQ Evaluations

Several plant system characteristics consistently emerge across IEQ frameworks as critical design factors including species, leaf area, leaf area density, planted area, density of planting, substrate type, thickness, and porosity, among other design variables. Many of these have relevance for multiple performance factors. For example, growth media design, or growing substrate, is an important consideration from both the perspective of sound absorption as well as VOC removal rates, but for different reasons. Increased depth of growing media might help the development of a rich root zone with diverse biota capable of more efficient breakdown of pollutants, while simultaneously improving sound absorption levels in a room. Species selection may have an influence in terms of photosynthetic rate and phase, while morphology, and leaf area have implications for acoustics, thermal and visual comfort, and CO_2 levels. Through more comprehensive understanding and characterization of the relevant plant metrics across multiple performance areas, we may uncover potential synergies and conflicting limitations to designing multivalent systems. Layering the complexity of relevant characteristics and performance metrics may benefit from visualization strategies to cross-link variables across heterogeneous data sets [74].

DISCUSSION / LIMITATIONS

Additional Assessment Frameworks Beyond IEQ

IEQ represents one aspect of the design factors within the BEP. Reflecting the true status of the decision making process in buildings, requires a comprehensive evaluation of the socio-economic factors and value structures across stakeholders [13]. If we were to take the case of green roofs as an example, these systems have seen a significant rise in implementation, an increase in 15% in North America since 2013, and substantial support from municipalities in recent years [85]. While their contributions to IEQ through thermal insulation are among their potential values [55, 86], it is their multivalent quality for both the public and individual building owners which contributes to their widespread acceptance; public services including stormwater retention, the mitigation of urban heat island, and carbon sequestration, with owner benefits from energy saving aspects or other impacts on occupant wellbeing [85]. It is in this same spirit, that green rating systems which attempt to "merge the priorities of economic prosperity, environmental quality, and social equity" [87] might allow for alternative valuation structures for indoor BIV.

Life Cycle Analyses. Frameworks that not only consider the effectiveness of the immediate context of IEQ but consider the lifecycle of material and energetic flow across the lifespan of the building, are increasingly necessary [88]. Investigations comparing the potential material, energetic and environmental costs of BIV as compared to other building materials is underway but is highly dependent on design instances and typologies [89, 90]. Metrics like life cycle analysis, embodied energy, and other factors similarly associated with the environmental costs for providing a structure's corresponding IEQ services, are critical evaluation systems required for a complete assement of BIV as compared to other building materials and systems designed to improve IEQ such as conventional HVAC systems, acoustic paneling, etc.

Energy. Of substantial importance to evaluating BIV would be to understand the relationship between plant systems and *energy use* and the extent to which any on particular instance or type of BIV can either (1) decrease the energy profile of the building either by offsetting higher ventilation rates by internally refreshing air and reducing the heating and cooling load on incoming outdoor air, or (2) the extent to which the presence of plants may allow for altering temperature set points.

Economic Factors. In terms of *economic costs*, multiple different characterizations can have relevance for built environment stakeholders, such as the comparison with current mechanical maintenance protocols, potential maintenance requirements (which could also count positively as job creation), and the replacement costs of plants versus typical filters. Also of note would be contingent valuation, or what people are "willing to pay" for this service [91]. A survey conducted by Hamilton et al., in 2016, to determine willingness to pay for improved ventilation or filters revealed that a majority of built environment professionals and users, including those with green building licenses, did not ultimately consider these improvements as valuable in terms of commonly cited impacts on productivity, absenteeism, or health, as compared with results from building modeling [92]. The extent to which built environment professionals and users might be willing to pay for indoor BIV for other aesthetic or health reasons might in fact tip the scales in favor of improved air quality.

Biophilia. LEED, WELL, LBC, GM, and BREEAM all include some aspect of *biophilic design* related to benefits to human health and wellbeing [20]. Biophilic design refers to the theory that humans are innately drawn to nature and other life [93]. Many studies have investigated the extent to which the physical presence of plants may improve physiological and cognitive effects, including increased energy and reduced stress [19, 21]. LEED, WELL, LBC, and GM attempt to quantify this biophilic impact through the metric of planting area. Assessing the impact of vegetation, and what aspects of living plants as opposed to other sensory manifestations of nature, influence health and well-being, is an ongoing area of research.

Ecosystem Services. The ecosystem services framework was formalized by the Millenium Ecosystem Assessment (MEA) to assess the links between the ecosystem and human health and well-being in a format that would speak directly to decision makers and stakeholders. The MEA defined ecosystem services as the benefits people obtain from the ecosystem including provisioning, regulating, cultural, and supporting services and has become largely mainstream in both regional planning, as well as discussion on urban green infrastructure. A thorough review of the effect of exterior urban green infrastructure on indoor environments was conducted by Wang et al., in 2014, [91]. Lyytimäki is the first to link the application of this framework to indoor ecosystem services, though without particular connection to indoor vegetation [94]. The catergory of Regulating Services could incorporate the entirety of the IEQ Framework and further include wastewater remediation and biophilic or other health benefits, while other catergories might encompass food or material production or aesthetic benefits. The extent to which any of these ecosystem services can be coupled at a scale which can show impacts on health and wellbeing is critical for future work. It should be noted that this framework is often criticized for its focus on valuing ecosystems in relationship to human benefits, rather than having intrinsic value [95].

Negative Effects / Other Costs. A comprehensive framework may not be complete without including an accounting of unwanted effects. In the context of other frameworks, several sources insist on the need to include disservices or costs in order to create a full picture of a method for assessment [96].

The Lack of Common Data to Extrapolate Frameworks and the Problem of Complex Data Management

The proposed scope of correlated performances is quite large, and yet it is representative of the decision-making frameworks employed by built environment professionals in practice. Many acknowledge the need for both inclusion of multiple functional performance metrics and variable selection and testing protocols, as well as the integration of study areas that have a direct or indirect relationship with each other [34, 64, 71]. However, working across multiple disciplines not only requires multiple teams with a diversity of expertise across performative categories, but requires the creation of common ontologies [74]. Because existing data presents in multiple formats and indicators, tracking common biophysical metrics across fields which use the data in very different ways makes this kind of multivalent evaluation difficult to achieve. The lack of reporting standards and multiple definitions in different fields may create too many “categories" and terms, making useful meta analysis difficult, and creating complexity that overshadows potential synergies.

The Difficulty of Extrapolation of Laboratory Scale Data to Building Scale and The Difficulty of Conducting Building Scale (Integrated Systems) Research Tracking Multiple Functions Simultaneously

Historically much of the work in indoor BIV began with the extrapolation of research conducted in isolated performance categories, often in controlled chambers within laboratory settings. However, fundamentally, the community of researchers and built environment practitioners are looking for evidence of the ability of these systems to perform at scale and within the complex open systems environment of a building. The ability to effectively quantify not only one factor but multiple functional impacts of any one system in an ecosystemic in-vivo context is challenging.

CONCLUSIONS / FUTURE WORK

Moving from IAQ to IEQ suggests that evaluating indoor BIV on measures of pollutant removal efficiency or indoor air quality effectiveness alone are insufficient to analyze their potential. The adoption of a more inclusive and comprehensive IEQ framework might show more potential for value, by better reflecting the complex interactive behaviors and requirements of occupied buildings [97]. In exploring the potential synergies for plant systems characteristics to achieve multiple functional outcomes simultaneously, the value proposition for indoor BIV may shift. To realize the value proposition of indoor green infrastructural systems, the scope of standards and recommendations by research sectors and legislative bodies has to expand to include multiple assessments that include living systems behaviors across socio-environmental criteria.

Future work will require a systematic investigation of indoor plant applications in each respective category of IEQ In layering the ontologies of IEQ metrics with the implications for impact from various plant systems characteristics, we can attempt to map synergistic or competing performances. Such a systematic ontological process of creating a shared performance framework can and should be adaptable to a number of evaluative metrics beyond IEQ, layering different stakeholder values which can then be weighted and prioritized according to context. Such a framework would allow for trade-off analysis between plant systems characteristics and multiple potential functional outcomes, giving designers of the built environment evidence-based opportunities to explore novel BIV systems.

ACKNOWLEDGEMENTS

This work could not have been completed without the constant support and dedication from everyone at Yale CEA. With special thanks to Mandi Pretorius in particular for support in the development of common ontological frameworks.

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