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Evolving Frameworks Towards Identifying Challenges and Opportunities of Indoor Vegetation Systems

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ABSTRACT

Our planet is rapidly urbanizing, leading to significant biodiversity loss. In architecture and urban planning, public and private developers are beginning to integrate vegetation into built environments 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 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. The value of such bioremediation systems, as well as the reliability of the evidence at the scale necessary to advocate for them, has often been obfuscated by the extrapolation of chamber-scale results with narrow scopes to the more complex contextual factors present with whole building matrix behaviors. To establish more systematic frameworks for evaluating building-integrated bioremediation and vegetation systems, shifting towards more comprehensive Indoor Environmental Quality 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 life-cycle analysis (energy, water, material use), potential health benefits (diverse microbiome, biophilia, etc), and other stakeholder frameworks (ecosystem services, etc) or value systems could offer more holistic 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

Perhaps it is in the spirit of growing environmental consciousness alongside emerging research that the building industry is experiencing increased social and market driven expectations, and in some cases legislative incentives or mandates, 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. As interest in indoor BIV expands, architects and other decision makers within the built environment require methods of evaluating systems in order to make actionable decisions on their implementation in building projects. If not properly characterized, there is a risk to introduce

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unfounded systems into buildings, or alternatively handicap what could be potentially effective solutions. It is in this context of the pressing need for metrics to evaluate indoor BIV, we are investigating the implications of moving from Indoor Air Quality (IAQ) to Indoor Environmental Quality (IEQ) performances for indoor plant-based systems. We are summarizing evidence in distinct fields of IEQ and highlighting the need to reframe those assessments through the lens of ecosystemic interactions across not only IEQ but with additional metrics from the standpoint of whole building delivery.

On the Challenges of Maintaining Current Mechanical Building Practices

With an increase in urbanization[1], a growing majority of people are spending 87% of their time inside buildings [2], relying on them to provide comfortable and healthy indoor environments. Before the twentieth century, buildings were not as heavily dependent on mechanical and electrical systems as they are today. Passive systems and strategies were the prevailing method for regulating indoor thermal comfort and air quality. In particular, natural ventilation was the prevalent methodology for revitalizing air within interior spaces [3]. Subsequent developments in building air handling systems and materials throughout the modern era increasingly tended towards the elimination of direct, distributed ventilation in favor of centrally controlled mechanical strategies that favored the performance criteria of predictable reliability and homogeneous separation from the fluctuations of climate. With the assumption that we can isolate our spaces from the surrounding environmental conditions, the building industry has invested and promoted envelope enclosures heavily dependent on mechanical systems and artificial filters. Mechanical heating, ventilation, and air conditioning (HVAC) has been the industry's standard recommendation for regulating thermal comfort and air quality in buildings for the last few decades, with well-known established performance aspects.

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 [4].Following the energy crisis of the 1970s, ASHRAE published *Energy Conservation in New Building Design 90-75,* the first standard reflecting increasing concerns on energy use[5]. Now, energy use analysis and energy commissioning is a critical part of evaluating system and building design layered ontop of and traded with indoor environmental functionalities. While some prefer to separate the criteria [6], from the standpoint of whole building delivery, energy cannot be separated from indoor environmental quality performance.

Additionally, the unwanted byproducts of these 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, noise, inadequate oxygen to carbon dioxide (CO_2) mass balance, and unsatisfactory humidity levels in heating degree months[7-9]. 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[10, 11]. Moreover, 80% of building occupants remain dissatisfied with indoor comfort [12].

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 come under increasing investigation. Emerging data suggests that the filtration of airborne pollutants in HVAC systems has a potential to decrease indoor microbial diversity [13]. Within the context of urban air quality patterns emerging data is pointing towards a co-relationship between low ambient biodiversity and health impacts such as asthma rates and potential pathogen prevalence [14-16], although these studies remain predominantly related to outdoor air streams. 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[17, 18]. These health and wellbeing concerns, along with energy conservation policies, have redefined the certainties and undoubted beliefs of the building industry and have opened the door for alternative strategies.

Multivalent Potentials for Bio-mechanical Alternatives Across Individual IEQ Categories

In response to some of the discussed limitations of mechanical systems, vegetation-based installations have emerged as a potential alternative strategy towards benefiting multiple indoor environmental quality factors. Biomechanical-hybrid systems for the production of various controlled "ecosystem services" inside buildings have been in development since the early 1950s. Studies have included oxygen production for space habitats through the use of algae based systems [19, 20], and indoor plant-based systems in development for the indoor production of agriculture, the production of energy [21], and even indoor the treatment of grey and black water [22]. Systems which are meant to regulate the interior environment in terms of an "indoor environmental quality" framework have also emerged, perhaps most notably in the area of indoor air bioremediation for the control of indoor air quality. 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 [17, 23-25], has arguably brought research in indoor air biofiltration into the public forum 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 in this area of research. Research over the past four decades suggests that indoor plant-based systems may provide opportunities to metabolize or sorbe certain pollutants through interaction with leaf structures and microbes in the root rhizosphere[17, 25-27]. While it has been demonstrated that microbes can metabolize VOCs in other contexts[28, 29], 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 and growing media sequestration [26, 30].

As interest in these systems have increased, emerging research in indoor BIV systems shows promise in multiple categories of the IEQ framework 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 acoustic comfort, thermal comfort, indoor air quality, and visual comfort [31]. In additional metrics of air quality, the ability for the leaf area of plants to photosynthesize opens up investigation into the degree to which they may participate in CO2 mass balance in indoor spaces[32-35] though species, circadian rhythms, and microbial respiration among other factors such as water availability and light intensity also participate in the determination of CO2 mass balance [35]. Much of this research exists outside the domain of bioremediation which may contribute to evaluating these systems with incomplete information.

Still others look to the potential for cooling and increased humidity from evapotranspiration [36, 37] or to impacts on acoustic performance[38-42]. In terms of visual comfort, human comfort levels are often contrasted with the functional mechanisms of the plant, particularly the lighting levels required for photosynthesis [43]. In response to health and wellbeing concerns, the introduction of plant-based microbial communities might have implications on supporting a diverse microbiome towards human health and well-being impacts [14, 15, 44, 45] as well as potential biophilic benefits [17]. 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, alongside a growing body of evidence to support the connection between plant-based systems with multiple values in the built environment process, there remain many criticisms and questions of the demonstrated performance of these systems. Standards bodies 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" [11].

Efficiency versus Effectiveness. The critical response to early experimentation has largely been a criticism of context. 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* [46]. 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 in attempting to scale-up chamber results to typical residential volumes resulted in an unreasonable number of plants [47, 48]. The comment suggests that the appropriate assessment would be the mass of pollutants removed per hour per plant as a measure of *effectiveness*. More recently in 2019, Cummings and Warring echoed these concerns, translating previous experimental results into Clean Air Delivery Rate (CADR) normalizing removal efficiencies by relevant volumes [49].

Typological Differences. Contributing to the confounding factors in understanding these systems is the fact that there are a range of 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 of 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. For example while the Cumming and Waring paper reported ineffective removal rates of potted plants, they go on to state that systems which actively draw air through the root systems of plants "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" [49] 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.

Multi-stakeholder Costs and Disservices. In addition, design considerations require performance evaluation that addresses additional potential disservices from built environment stakeholders standpoint. One major concern includes the potential of mold spores from overly damp or humid spaces [50]. 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 being able to control consistent airflow. Indeed, one systematic study showed no increased presence of pathogenic mold [51]. Plants have also been cited as a potential source of VOCs [47], 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 introduce pathogens or complicate CO2 mass balance [52]. The list of concerns goes on, including the extent to which any particular system may cause structural damage due to root incursion, introduce unwanted pets, odours and allergies, or require excessive energy, water, or maintenance resources [18]. These are significant considerations critical to built environment decision makers, but are only manifest when expanding the necessary performance criteria of these systems beyond the disciplinary borders of single air quality functions.

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 bounded by domain specific problems. Currently, indoor plant systems research, much like individual categories of IEQ, remain focused on one performance metric at a time, reporting on values commensurate with other systems of the same category. In the case of plant-based air remediating systems, the focus on experimental reporting in percent removal rate closely mirroring MERV rather than CADR has stagnated some of this research. Researchers in this arena seeks to justify the potential of these systems by addressing the projected reduction in energy costs of ventilation [24, 53] or by comparing these systems with physiochemical filters such adsorption filters, photocatalytic oxidation cleaners, and ozone generators [54]. Others in the scientific and built environment community have responded in kind with comparisons to the metrics and standards used to analyze mechanical systems, namely the efficiencies of mechanical ventilation [49, 55] 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 an evaluation criteria in itself, an indicator which is one step removed from baseline biophysical measures of IAQ which specify certain levels of pollutant concentrations [6, 56]. Such assumptions become problematic when air filtration is advocated over ventilation when energy or outdoor air quality is of concern [11]. The comparison to ventilation sets up an "all or nothing" scenario for air quality. System designers seek out the scale at which plants may match ventilation or entirely compensate for respiration through photosynthesis for example might miss opportunities for indoor vegetation to participate in making noticeable impacts on human health. For example, one study estimated the area of one particular design of green wall required 5m2 of area to support the respiration of one occupant, but a smaller area of 1m2 was able to create reductions of CO2 which would have an effect on human health metrics [33]. These questions of appropriate or valid metrics or benchmarks highlight the concern that the evaluation system used to understand air quality is predicated on existing mechanical paradigms, even at the expense of other critical requirements such as energy and water use, and material and resource consumption.

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 or ecosystemic performance in multiple aspects of IEQ including air quality, thermal, acoustic, and visual performance. The industry already recognizes the necessity to move from evaluating the performance of isolated systems to focussing on more effective 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 [57]. Currently, separate building codes and guidelines are considered as problem instances to be solved mostly in isolation from the multiple other building issues sacrificing the potential for holistic environmental and sociological solutions [58]. IEQ alongside other interdependent factors in the Built Environment Process (BEP) need to be negotiated throughout the design and construction administration phases [59, 60]. Historically, when buildings were less intricate structures prior to the intense mechanization of buildings, the architect was the center of the BEP as a single domain expert could manage the complexities. 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 within the BEP. Architecture, Engineering and Construction (AEC) design professionals who operate at this nexus of information need more viable frameworks to evaluate multiple ecosystemic 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 [58] within the current mechanical paradigm. If plant-based living systems were added to the matrix of systems requirements at scale, the degree of complexity and domain expertise would be significantly compounded.

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 biologically-based building systems 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 [61]. 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 [5, 62, 63].

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 [64]. 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, CO2, 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 [23, 25, 53, 65-68]. 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 [69].

CO2 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 CO2 exchange, however it is not the only driver. Photosynthetic rates are dependent on species, lighting intensity, watering regime, and other factors [70]. However, as CO2 exchange and photosynthesis are measured in number units (umol/m^2/s) [71], 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 [72]. 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 [36, 73, 74].

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 [41, 75]. 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 [38-42].

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 [43, 76]. 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

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 CO2 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 [64].

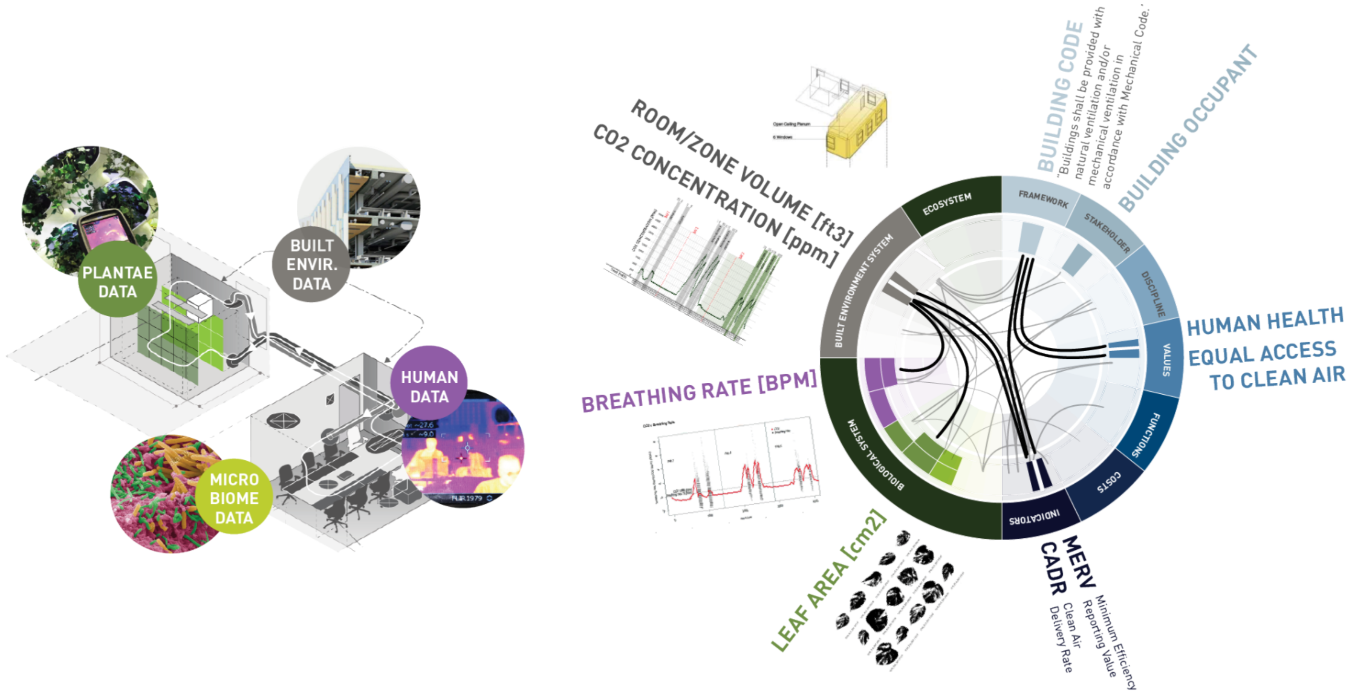

Figure 1. Parametric approaches to cross-linking multidisciplinary heterogeneous datasets including plant system characteristics, biophysical measures of Indoor Environmental Quality, indicators, values, and frameworks (Dyson et al., 2022)

DISCUSSION / LIMITATIONS

Additional Assessment Frameworks Beyond IEQ

IEQ represents one aspect of the design factors within the built environment process. 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 within the built environment process, including among other metrics, material and equipment life cycles, energy use, waste and byproducts, etc. for the duration of a building's useful lifetime [12]. 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 [77]. Until we introduce measurements like life cycle analysis, embodied energy, and other factors similarly associated with the environmental costs for providing a structure's corresponding IEQ services, evaluation systems would lack the tools for a comparative analysis between different strategies to achieve these indoor services.

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 [78]. While their contributions to indoor environmental quality through thermal insulation are among their potential values [72, 79], 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 [78]. It is in this same spirit, that green rating systems which attempt to "merge the priorities of economic prosperity, environmental quality, and social equity" [80] might allow for alternative valuation structures for indoor BIV. In LEED, Pilot Credit SSpc158 for example, offers a credit for onsite carbon sequestration through plantings, making use of the online tool iTree which offers an evaluation of site plantings in terms of not only carbon sequestration, but in terms of energy savings for the building from shading, windbreaks, and evapotranspiration, stormwater capture, air pollutant removal rates [81]. The extent to which indoor green infrastructure can make contributions to carbon sequestration within indoor environments is not yet well understood or quantified.

Energy. There are a few more well established frameworks within the built environment process which we can use to evaluate BIV. Of substantial importance would be to understand the relationship between plant systems and *energy use* and the extent to which 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*, the development of multiple different characterizations are essential to acceptance by 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 [82]. 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 [83]. 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* in their frameworks related to benefiting human health and wellbeing [18]. Biophilic design as engaged by these multiple green rating systems, refers to the theory that humans are innately drawn to nature and other life [84]. When applied to the built environment, this often indicates design for connection to nature in some way, often, though not always, in terms of the integration of actual vegetation. Many studies have investigated the extent to which plants improve physiological and cognitive effects, including increased energy and reduced stress [17]. LEED, WELL, LBC, and GM attempt to quantify this biophilic impact through the fundamental metric of planting area. Assessing the impact of vegetation, and what aspects of living plants as opposed to other sensory manifestations of nature, influence human health and well-being, is an ongoing area of investigation.

Ecosystem Services. The ecosystem services framework was formalized by the Millenium Ecosystem Assessment (MEA) in an attempt 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, [82] while Lyytimäki is the first to link the application of this framework to the production of ecosystem services indoors, though without particular connection to indoor vegetation [85]. Through an application of this framework to indoor BIV, we can begin to categorize services claimed by various systems using this framework. Provisioning Services might include Food in the case of indoor agricultural and rooftop gardens, Pharmaceutical, or Material Production. Regulating Services could incorporate the entirety of the IEQ Framework and further include grey and/or black wastewater water remediation. Cultural Services might include aesthetics. The extent to which any of these ecosystem services can be coupled at a scale which can show impacts on human health and wellbeing is critical for future work. For example, high production yields for Controlled Environment Agriculture often require higher light and CO2 levels than acceptable for most interior environments. It should be noted that this framework is often criticized for its focus on the valuation of ecosystems in relationship to human benefits, rather than having intrinsic value in themselves [86].

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 [87].

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 [31, 56, 61]. 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 [64]. 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 plant-systems 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 [88]. 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 indoor environmental quality. In layering the ontologies of indoor environmental quality 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.

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