The 16th Conference of the International Society of Indoor Air Quality & Climate (Indoor Air 2020)
COEX, Seoul, Korea | July 20 - 24, 2020

Paper ID ABS-0368 ISBN: …………………….

Microbiology of the Built Environment (MoBE) for architects, a review of applied spatial metrics for application in healthy building design

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SUMMARY

Humans spend up to 90% of their time in indoor built environments. There is recognition and academic consensus that architectural design impacts both the sources of the microbial communities, (via activity and mix of occupancy), and the processes that affect them. Microorganism have been shown to negatively impact on human health in buildings, as established by research in the field of Healthcare Associated Infection (HAI). Researchers conducted a systematic literature review to investigate the extent to which the emerging field of the microbiology of the built environment (MoBE), takes into consideration the spatial metrics which are of interest to the generators of the built environment, with specific reference to the architectural community. The literature review found that the majority of MoBE studies collect some architectural, engineering or related data, such as occupancy, occupant activity and spatial data, but the objectives and methods varied significantly, which poses a barrier to comparing studies and deriving conclusions useful to the built environment practitioners such as architects. Furthermore, where built environment data is collected, it is generally not used in analysis and reporting, and is therefore limited in its practical utility in building design, which influence the practical application for built environment practitioners.

KEYWORDS

Architecture, Spatial planning, Microbiome, MoBE, HAI

INTRODUCTION

Architectural factors and health in MoBE studies

Brown, Kline, Mhuireach, Northcutt & Stenson (2016) postulates that quality architecture should be seen as a public health service considering the potential impact built environment has on human health. However, to realise this health conscious approach of "bioinformed" buildings that foster well-being, architects need scientific knowledge that addresses the conditions and constraints of their work. Microbiology of the built environment (MoBE) research represents a prime opportunity for such design science collaboration (Brown et al. 2016:1). Adams et al. (2016) report that current research has highlighted the potential connection between the indoor microbiome and health, although, with a few notable exceptions, most recently published publications establish correlation, not causation.

Noteworthy examples found of a direct link between specific microbes in the indoor environment and acute infections, are Mycobacteria Tuberculosis (Yates, Tanser & Abubakar 2016), and influenza, and the fungus Aspergillus where the indoor ventilation system can serve as a transmission route for pathogens. Kelley and Gilbert (2013) recommend that a deeper understanding of indoor microbial diversity inform public health policy, particularly in settings with many immune-compromised individuals such as hospitals, intensive care units and nursing homes.

Humans spend the vast majority of their time - up to 90% - indoors (Klepeis et al. 2001). Numerous studies have shown the presence of human associated biota in indoor spaces. Lax et al. (2017) indicated that, in fact, leave behind our microbial signature for the next occupant. Global trends in urbanisation is increasing indoor living (Höppe & Martinac, 1998). Yet our understanding of the indoor environment is limited (Hospodsky et al. 2012). The built environment are complex ecosystems, host to a wide variety of organisms and trillions of microorganisms (Rintala et al., 2008; Tringe et al., 2008; Amend et al., 2010) which share these spaces with us. The large percentage of time, that we spend indoors in our life time, will invariably mean that the manner in which we design, use, interact and shape our indoor environments will impact on our health. This collective indoor environmental ecosystem is known as the microbiome of the built environment (MoBE). Five key and critical literature reviews conducted by peers in the field which exhaustively summarised various aspects within the MoBE field were identified (Larsen et al., 2012; Kelley & Gilbert, 2013; Ramos et al., 2014; Adams et al., 2015, 2016). These reviews include modelling approaches and culture analysis, sequencing and sampling, built environment tools for data collecting, meta-analysis of various datasets for various fields in various studies identifying challenges, similarities aimed at identifying patterns and the connection between studies. There is a postulated link (Levin & Corsi, 2012) and some limited anecdotal evidence (Ramos & Stephens, 2014) of the association between various architectural design features such as building materials selection and spatial design on MoBE (Kembel et al., 2013). This literature review does not intend to copy and repeat what has already been disseminated regarding MoBE generally. It focuses specifically on the subset of literature in which spatial metrics – i.e. topics of relevance to the architectural discipline – is reported or discussed, in order to identify research gaps in the field of architecture from current MoBE literature.

METHODS

Scopus, ISI and Google Scholar databases were systematically searched with the following keywords: MoBE, architecture, HAI, health, spatial planning, building ecology, indoor quality. Positional pieces were excluded from the study. A critical review was performed on peer-reviewed journal articles identified in the literature search. Due to a lack of standard applied methods for the built environment in BE biome studies, and confirmed by Ramos et al. (2014), in their systematic review, the following thirteen research questions were devised and applied to literature to extract relevant data for the analysis and categorisation of architectural factors, microbiological factors, and combinations thereof: 1). Did the study investigate building and microbial relationships? 2) Which engineering and architectural factors were considered? 3) Was reference made to architecture and spatial planning, and how was this applied? 4) Was reference made to building ecology and microbial environments, and how was this applied? 5) The study period: Short term (- 2 days) Londitudal (+ 3 days) 6) The study site: Single study site or multiple sites? 7) What sampling methods were utilised for the built environment, and how was this applied? 8) What sequencing methods were used? 9) Which indicator microbes were identified in the built environment? 10) What sampling methods were utilised for microbiology, and how was this applied? 11) Did the study consider an interdisciplinary approach by different fields? 12) What were the challenges? 13) Did the study discuss or make reference to human health and wellness or infection prevention and control in the built environment? Our analysis further distinguished between the building environmental factors and building spatial factors identified.

FINDINGS

From the literature reviewed in excess of 50 articles it was determined that only four studies have documented or considered spatial factors and spatial related studies, even though numerous investigations have identified the impact of human occupancy as major driver of indoor microbial communities through a combination of direct human shedding, resuspension from flooring, and emission from respiratory activities reference include: (Hospodsky et al., 2012; Lax et al., 2017). Not all the reference could be incorporated into the paper (due to length limitations)

Human activity: Human activities, the way in which we utilise were found to be critical determinants of microbial diversity in spaces through touch (surfaces), breathing (air quality) and travel, reference include but not limited to (Oberauner et al., 2013; Flores et al., 2011; Chen et al., 2006).

Architectural factors identified: The influence of the collective of these factors are difficult to determine as they vary in quantitative and qualitative data. Some studies have merely listed factors for information or conducted minimal qualitative observational versus studies that have performed quantitative data measurements. First, the qualitative factors are discussed, followed by the quantitative.

Qualitative factors - Building environmental factors: Adams et al. (2014) in a study on airborne bacterial and fungal communities in residence in the United States of America (USA), utilised questionnaires that were 'self-reported' on factors of unit floor plan (rooms and room types), inhabitants, and their behaviour, houseplant and use of humidifiers. Due to the nature of the data collection the following topics were invariant and therefore excluded: air treatment, daily occupancy, cleaning regime and opening of windows. The building typology was also factored, defined as matching residential units. with reference to the factors they reported on surfaces in various locations, where rooms also differed in bacterial communities based a common source, or where a different source or support the growth of different microbial communities. Whilst no building design spatial factors were documented, the geographic distance of samples provided strong indication that for both bacteria and fungi samples, separation by a few hundred meters *tended have greater compositional differences than samples closer together in space*. Of spatial interest was the reduction of *Deinococci, Alphaproteobacteria, Cyanobacteria, and Cytophagia from their greatest relative abundance outdoors decreasing as you enter the indoor spaces, whereas Gammaproteobacteria, Clostridia, Bacilli, Flavobacteria, and Actinobacteria increase in abundance as you move to the more internal rooms of the dwelling* (Adams et al., 2014, p.3). This community change by room type, with the presence of outdoor and indoor bacteria found in the building, indicate the influence of spatial layout and human activity, confirmed by the fact that bacterial composition varied by residential unit and room type. *Human-associated bacterial genus, Corynebacterium,* represented 11% of indoor sequences, making humans a source of indoor microbes.

Quantitative factors - Building environmental factors: Two studied focussed on healthcare typology were found in the literature search, as contributions to the collaborative Hospital Microbiome Project. Kembel et al. (2013) investigated the *airborne bacterial community structure and environmental conditions in patient rooms exposed to mechanical or window* *ventilation and in outdoor air* at the Providence Milwaukie Hospital. The built environment factors considered included ventilation source and related metrics, temperature and humidity. Specific ventilation metrics were studied and included: air changes per hour calculated for patient rooms taking into account room volume, air speed and volume flowing into the room through the window (window-ventilated rooms) or diffusers (mechanically ventilated rooms). To account for the different ventilation sources, measured microbial community dissimilarity was explained by authors in terms of each environmental variable after accounting for the ventilation source. No consideration to building design spatial factors were reported or studied. The study found that *building attributes, specifically the source of ventilation air, airflow rates, relative humidity and temperature, were correlated with the diversity and composition of indoor bacterial communities.* Similar to the findings of Adams et al. (2014) the relative abundance of bacteria closely related to human pathogens was higher indoors. In addition, the composition of the indoor airborne communities differed based on ventilation source. The mechanical source communities were distinct from outdoor air communities, and accounted for the major difference in community composition between rooms in the study. These finding are supported by previous studies which include but not limited to (Tang et al., 2009; Qian et al., 2010).

The first of two extensive architectural MoBE studies, Kembel et al. (2014) investigated a multi-use classroom and office buildings in the USA. Ramos et al. *(2015)* and Lax et al. (2017) (two publications for the same study) considered factors related to space type, building arrangement, human use and movement, and ventilation source. Further spatial and architectural attributes of each space was factored: floor level, location, floor area, air handling unit, ventilation type (natural or mechanical), human use patterns per space, ambient air temperature and relative humidity per space. The data were obtained by field observation (data sampling), a building information model and building plans. Building design spatial factors included design attributes of each space: function, form, and organization. The human use patterns for each space were estimated values based on a qualitative assessment of expected patterns of human diversity based on annual occupied hours in each space. This was the only study that referenced network analysis. Factors considered were 1) spatially connectedness of space: immediate and between pairs of spaces in the building 2) measures of network centrality for each space in the building: betweeness and degree. The researchers found that space size, relative humidity, and occupancy varied less across offices than across all rooms at the building-scale inferring the dynamic nature of shared indoor environments. Statistically the ventilation air source in offices had the greatest effect on bacterial community structure. Two pertinent findings from the study are the room type factor and spatial relationship factors (Kembel et al. 2014). The second healthcare typology study, first reported by Ramos et al. (2015) followed by Lax et al. in 2017 was for 10 patient rooms and two nearby nurse stations at a new hospital pavilion at the University of Chicago Hospital. The study design was developed as part of the Hospital Microbiome Project through workshops as reported by Smith *et al.* and Benjamin et al. (2013). The following built environment factors, intended to be comprehensive, were noted for inclusion in the study: occupancy, space use, user types, and user interactions in space measured by means of radio-frequency identification (RFID) technology. CO_2 concentrations were measured and used to estimate the percentage of recycled air. Various ventilation metrics of the heating, ventilation and cooling (HVAC) system (air-flow and filtration system for both pressure, CO_2 and microbial/viral community structure) were measured and recorded The project scope and sample size was discussed. Real time sensors and beam break sensors were used in walk ways in conjunction with inpatient stay and associated clinical data to record and measure occupancy. The need for spatial metrics was again emphasised, with reference to high spatial and temporal resolution observation of microbial and human occupant dynamics in order to enable more specific identification of the routes of transmission between building occupants and building infrastructure.

Ramos et al. (2015) reports on the findings of the Hospital Microbiome Project. An exhaustive data set on environmental metrics were recorded. The building design spatial factors and metric data was measured for measures of human occupancy and activity for the patient rooms. This was achieved by indoor CO_2 concentrations and infrared (IR) beam-break counters installed at the patient room doorways. The selection of spatial metrics and occupancy measures are supported by the investigative studies of Kembel et al. (2014); Hospodsky et al. (2012); Qian et al. (2012) and Lax et al. (2014). Lax et al. (2017. Ramos et al. (2014) conducted an extensive literature review of MoBE studies aimed at developing and recommending tools to improve built environment data collection for indoor microbial studies. Their review identified a number of building factor which is not mentioned in this paper due to length. In their paper, *methods to assess human occupancy and occupant activity in hospital patient rooms*, Dedesko et al. (2015) investigated a number of measures of occupancy and occupant activity in the Hospital Microbiome Project of 10 patient rooms. It was predicted that occupancy would have prominent effect on indoor microbial communities. They conclude that, for studies of short duration, activity cannot be sufficiently assessed with CO_2 applied methods. The authors recommend a combined beam-break and CO_2 method.

DISCUSSION

A number of studies have investigated the microbiome of the built environment but with far less rigour with regards to the built environment factors than the studies mentioned. (Frankel et al., 2012; Rintala et al., 2008; Tringe et al., 2008; Amend et al., 2010; Hospodsky et al., 2012; Horner et al.; 2004) and more. The omission of built environment factors studied in conjunction with microbiological characterisation studies result in underreporting of potential factors that influence the microbial community and limits the characterisation of the microbiome of building indoors. Unfortunately, they are far more in number than investigation that do provide built environment data as confirmed by Ramos et al. (2014). However, they still fundamentally contributed to the understanding and development of core theories of MoBE as we know it today. When considering the post-collection processing and analysis of building design spatial metrics, they are even less in number (Adams et al., 2015). Only four of the in excesses of 40 journal articles reviewed, and additional articles through the various literature reviews by the noted authors considered occupant activity and presence, despite recognition that human occupancy and user identification, human activity, space use and spatial relationships are significant drivers of the MoBE. Levin and Corsi confirms the position that *Human activities and patterns and building operation seem to have the greatest impact on indoor microbial ecology* (2012, p.4). Researchers recognise that building occupants directly, and, by extension, the architectural design (through factors of building design, planning, occupancy and use patterns) indirectly impacts on the microbial diversity and community composition of the building microbiome.

BE data sampling applications

As reported in the previous section, the application of building design spatial factors in most studies were not common and or omitted. However, studies that did apply a form of spatial analysis or considered a form spatial metrics are reported here. Adams et al. (2013) only reports the use questionnaires by self-reporting by resident. Kembel et al. (2014) reviewed building plans, conducted field observation and developed a building information model (BIM), collected data on human use patterns, and performed network analysis (spatial analytics) based on estimated qualitative assessments of expected patterns of human occupancy and diversity in space. Kemble et al. (2013) reports no spatial data collection. In their study in 61 buildings of various typologies for fungal growth, Amend et al. only considered a potential spatial metric of geographic distance between samples to correlate phylogenetic dissimilarity (2010). In the study of floor dust and resuspension, Hospodsky et al. only considered the internal movement of a single room, but only records occupancy (2012). Similarly, Qian et al. (2012) quantified size-resolved emission rates of airborne biological particles in a university classroom measuring occupancy. Meadow et al. (2014) reports only on the collection of occupancy data by technicians on site. Kelley and Gilbert consider the applications for building design spatial factors in sampling in (2013), and note a critical research gap in the successful characterisation of the indoor environment.

Research gaps and future investigations

Dispersal and niche based study focus will be required to define and promote healthy indoor microbiomes, (Kembal et al., 2014; Brown et al., 2016). A number of research gaps have been identified by various studies. Researchers have identified a critical constraint in that, scientific research can (and does) fail to inform architectural practice (Brown et al., 2016). Here the development of spatial analytic tools and design guidance models are paramount. The gaps in research due neglect of built environment factors and for this review spatial (both space and time) remains limited. The built environment represents a unique context and under-explored ecosystem, as in other microbial fields such a soil, marine etc., the built environment requires the development of standards for use in microbial studies. (Glass et al., 2013; Gilbert et al., 2012). With reference to spatial data, occupant activity and occupancy the findings of (Dedesko et al., 2015) can be used to better understand occupant behaviours and their effect on the indoor air and surface parameters in an indoor study environment. Although a number of approaches have been analysed, there is still a gap in the literature. The majority of existing methods are based on estimations of occupancy whereas real-time rates would provide greater value in dynamic microbial community characterisation. Similarly, much less attention has been given to detecting occupant activity (their movement in space), despite evidence indicating that such movements have a stronger effect than occupancy on certain aspects of indoor air quality. The limited measure of occupant activity (at most only by gate crossing/threshold crossing) presented in the various studies indicate an opportunity for new approaches in spatial syntactical measures. When considering niche space in micro environments as noted by (Kelley et al., 2013; Kolter, 2006, 2010), it also infers finer detail studies in human activity and conversely the spatial function or probable activities in space in real time. A modelling tool for consideration for future studies could be the novel application of Space Syntax (Nice, 2019).

CONCLUSION

The literature search found that the majority of MoBE studies collect some architectural, engineering or related data, such as occupancy, occupant activity and spatial data, but the objectives and methods varied significantly, which poses a barrier to comparing studies and deriving conclusions useful to the built environment practitioners such as architects. The study further found that even where built environment data is collected, it is generally not used in analysis and reporting, and is therefore limited in its practical utility in building design. Finally, research results may not reach built environment practitioners; may not address questions that seem important or relevant to architects and then fail to synthesize their findings into design tools or guidelines (Brown et al., 2016).

6 ACKNOWLEDGEMENT

The author would like to acknowledge the financial support provided by the CSIR.

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This is not a comprehensive list of reference (considering this is literature review), upon request the author will provide the literature set.

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