Review Research

THE PHYLLOSPHERE, INDOOR MICROBIOME AND HUMAN HEALTH

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ABSTRACT

A healthy indoor environment is very vital as humans spend a greater percentage of their life within built environments. A healthy and quality environment is determined by the biodiversity of and features of the natural environment. The indoor environment just like every other environment possesses a unique community of microorganism which depends on the level of contact between the environment and natural sources. Plants are significant sources of microbial diversity in an environment. There is an interplay between the phyllosphere and the troposphere where the microorganisms released from the phyllosphere perform several beneficial effects consequently, improving human health. The indoor environment must however be enriched with natural sources of microbial release to enhance its biodiversity. This paper therefore focuses on the phyllosphere as a natural source for enhancing indoor biodiversity, the interplay between the phyllosphere and its surrounding environment and its implication on human health.

Keywords: Phyllosphere, indoor, environment, microbiome, health.

MICROBIAL COMMUNITIES OF PLANTS

Plants relates with a broad and varied group of microorganisms including bacteria, viruses, fungi, and oomycetes that colonizes their tissues, with bacteria being the most abundant. Plants derive the bulk of their microbiota from the environment and the soil which harbours highly varying microorganisms dominated by *Verrucomicrobia, Bacteroidetes, Acidobacteria, Actinobacteria, Proteobacteria*, and *Planctomycete* (Fierer, 2017). Seeds can house several microbial communities, and these seed-borne microorganisms perform a vital duty in the plant's early development and growth (Truyens, 2015). The seed also provides an effective way to spread and transfer the microorganism from one plant to the next. Most pathogens of plants are transmitted by seeds like the *Aspergillus flavus* ascomycete and the *Rhizoctonia solani* basidiomycete. Nonetheless, beneficial microorganisms and commensal are also found in plant seeds, e.g. beneficial fungal species *Epichloë* and *Alternaria* and bacteria such as *Curtobacterium* and *Paenibacillus* (Harrison *et al*., 2018).

Another very important source of microbes is the substratum on which plant growth takes place. It is usually the soil (Bulgarelli *et al*., 2015). Specific microbial sources such as air, precipitation and soil are the target of the above-ground plant tissues (Muller, 2016). Microbiota study of *A. Thaliana* and crops such as maize, barley, rice and citrus have shown that Actinobacteria and Proteobacteria dominate the plant microbiota, and also Bacteroidetes and Firmicutes at lower dominance (Xu *et al*., 2018).

The rhizosphere

Most root microbiota are distributed horizontally, i.e. they are collected from the soil ecosystem which harbors a wide variety of microorganisms (Fierer, 2017). The rhizosphere is described as a microbial activity hot spot (Compant *et al*., 2019). Kawasaki *et al*. (2016) indicated that *Sphingobacteriales*, *Burkholderiales,* and *Xanthomonadales* dominated the rhizosphere of *Brachypodium distachyon* (a model for wheat), while *Bacillales* dominated the soil. Root exudates like those of amino acids, organic acids, plant growth regulators, fatty acids, phenolics, nucleotides, putrescine, carbohydrates, vitamins and sterols influence microbial composition around the roots (Olanrewaju *et al.* 2019).

Bacterial endophytes enter the root tissues through passive processes, root cracks, lateral root points and active mechanisms as well (Hardoim *et al*., 2012). Many factors affect the rate of colonization and transmission of endophytes within plants, including the ability of the endophyte to colonize the plant and the distribution of plant resources. For example, Acidobacteria, Proteobacteria, Bacteroidetes, Planctomycetes, Actinobacteria, Firmicutes, Verrucomicrobia, Gemmatimonatedes and Chloroflexi were the most abundant phylate found in grape vine roots (Burns *et al*., 2015). Maize roots is found to be dominated by Firmicutes, Bacteroidetes and Proteobacteria (Correa-Galeote *et al*. 2018).

The phyllosphere

Certain phyllosphere areas include the anthosphere: which is the flowers ' external environment, the spermosphere: the seed's external environment, the caullosphere: the stem's external environment and the carposphere: the internal fruit ecosystem (Compant *et al*., 2019). The microbial population of the plant, usually found in numbers ranging from 10^6 to 10^7 cells / cm^2 / g) of soil, is dominated by bacteria (Andrews and Harris, 2000). The bacterial population of the planetary phyllosphere may be as large as 10^{26} cells (Lindow and Brandl, 2003). Apparently, these bacteria are numerous enough in aggregate to influence global activities and the actions of their host plants.

THE INDOOR MICROBIOME AND THE HUMAN HEALTH

The indoor microbiome

Indoor environments are usually greatly affected by bacteria associated with human as a result of the activities of human and the high emission levels of up to 10 bacteria per person-hour from aerosols (Qian *et al*., 2012). The human microbiome is formed by the bacteria, fungi, and viruses that colonize indoor environments and can fundamentally alter human health trajectory. The indoor microbiome can affect the development of children's immunology, physiology, and neurology. Children will spend 98% of their first year of living indoors with an extremely impoverished exposure to a complex microbiota that would usually train a healthy immune system and promote good physiology and neurology (Gilbert and Stephens, 2019).

Microorganisms harboured in built environments can be seen in air, in water systems and on surfaces. These microbes arise from and are transported by living creatures residing within that environment, such as human occupants, plants, pets, and pests which possess individual distinct microbial communities. The microbial community of an indoor environment is therefore affected by several factors which can be broadly classified into two viz: design choices and behavioural choices. The design choices that impact microbial communities include: flooring content, ventilation system, humidity / relative moisture, occupant density and location of buildings while some behavioural considerations include: cleaning procedures and duration, presence of animals, presence of plants and overcrowding.

Relationship between indoor microbiome and human health

Built environments are the predominant ecosystems colonized by man in industrialized areas of the world and human microbiome may be influenced by the environments in which people live, which may consequently affect human health. Environmental microbes, for example, can proliferate in the human host's niche-specific ecosystems such as in gut, skin and airways.

In developed parts of the world, human spend a major part of their lives indoors (Gilbert and Stephens, 2019), which can limit the microorganism diversity to which they get in contact with. The exterior of a building (the foundation, windows, walls and roofs) divides the indoor and outdoor worlds, thus minimizing contact with outdoor thriving microbes and inherently modulating contact to indoor thriving organisms. Nevertheless, it is not well known to what degree the indoor microbiome leads to this diversity or lack of it. People who spend more time outdoors in economically disadvantaged and less developed communities may have higher risk of infectious disease and greater risk of infant mortality (Hanski *et al*., 2012, Clemente *et al*., 2015).

This may, however, be as a result of their health status when contact with infectious agents is made than the exposed microbial nature. Some studies implicated the beneficial effects of exposure to different microbes on the immune system (Sordillo *et al*., 2010; Behbod *et al*., 2015).

Under certain conditions, indoor microorganism, their metabolites and components could trigger both positive and negative health effects (Quansah *et al*., 2012; Lai *et al*., 2015). The features of an indoor environment, community of microorganism present and human activities in that environment may affect the amount of exposed microorganism which may invariably decide the adverse, beneficial or neutral effects on health. Several factors such as the features of a building, life stage exposed individuals, exposure dose, route of exposure and genetic sensitivity determine the beneficial or detrimental effects of a microbial community at a given time. Microorganisms that improves the human immune system are primarily potential beneficial microorganism (Kelly *et al*., 2005), they release little molecules that transforms human health (Neish, 2009) or initiates other helpful functions of the human health (Rook and Lowry, 2008; Reber *et al*., 2016). Sick Building Syndrome (SBS) is a situation where time spent indoor in a particular building, room or zone affects human health or comfort and is characterized by headache, nausea, fatigue, personality changes e.t.c. without any specific course except time spent in the building (Brilli *et al,* 2018, Amoatey *et al,* 2020)

The outdoor environment harbours diverse microorganisms which possess richer microbial diversity than the indoor environment. The difference in this microbial diversity is connected to the fact that outdoor environment has more vegetation and more varying source of microbes that contributes to its diversity. Several factors such as cleaning procedures, building materials and design choices affects the microbial diversity of the indoor environment. Less contact with natural sources is the key factor militating against the microbial diversity of the indoor air in accordance to the highly recognized “hygiene hypothesis” and “biodiversity hypothesis (Haahtela *et al*., 2015).

Degradation of harmful compounds by indoor microbes

Within the built environment, viable indoor microbes are likely to metabolize chemicals. Variety of chemicals seen in furniture or household products, such as perfluorooctanoate (PFOA), perfluorooctane sulfonate (PFOS) and bisphenol have an effect in the endocrine function (e.g. risk of diabetes or glucose metabolism) and growth in children, as well as the chance of obesity (Heindel *et al*., 2017). Several investigations has shown that microbes in the environment can degrade these chemicals and other chemicals with destructive endocrine potentials, which may produce more bioactive chemicals and may also decrease toxicity (Janicki *et al*., 2016; Vejdovszky *et al*., 2017). The skin’s community of microorganism promote the state of health of the body via immune responses that preserve health or, in some situations, may modulate disease conditions (Barnard and Li, 2017).

Effect of indoor microbes on respiratory conditions

Dust from areas where dogs reside and the microbial communities within it reduce symptoms of atopy in mice (Fujimura *et al*., 2014). The mode of action is suggested to be characterized with the microbial communities related with animals. Gut microbiota differences such as accelerated concentration of *Lachnospira* spp., *Faecalibacterium* spp and *Veillonella* spp from the Firmicutes phylum (Arrieta *et al*., 2015), seem to have a function in asthma protection within the first three months of life (Lynch *et al*., 2014). In addition, there is a proposed relationship between high bacterial exposure and fungal diversity at tender age and protection from wheeze and asthma (Ege *et al*., 2011; Dannemiller *et al*., 2014; Tischer *et al*., 2016). There are reports on the antagonistic effects of microorganisms, their metabolites and their constituents on the onset and progression of allergies and asthma, (Quansah *et al*., 2012; Lai *et al*., 2015). Also, there are reports of protection from the onset of allergy and asthma conditions as a result of exposure to microbes (Sordillo *et al*., 2010; Behbod *et al*., 2015). Increased atopy rate has been associated with decreased exposure to some species of *Bacteroidetes* and *Firmicutes* associated with house dust (Lynch *et al*., 2014). The absence of these bacterial phyla which is usually found in the mammalian gut indicates a decrease in stool present in the environment.

Indoor pathogens and infections

Fomites are seen in the transmission of infectious disease, and transfer of pathogens by aerosol in various built environments can occur ((Julian, 2010, Wong *et al.,* 2010).

Fungi are a source of various constituents beneficial to health, however, some allergens and other antigens found on indoor fungi can aggravate respiratory symptoms Increased exposure to certain non-microbial allergens in early life, can help in increasing protection and tolerance from allergic responses (Du Toit *et al.,* 2015). It is however not known if tolerance can take place when there is exposure to fungi allergens in the early stage of life. Summarily, fungal exposure in the early years of life may worsen the children's health Jaakkola *et al*. (2013) reported that rhinitis, other allergic rhinitis and rhinoconjunctivitis can arise and or be exacerbated by dampness and exposure to mold at home.

THE PHYLLOSPHERE AND INDOOR MICROBIOME INTERPLAY

Humans contribute immensely to the availability of microorganisms in the indoor environment (Mahnert *et al.,* 2015). The phyllosphere should be of key concern in examining indoor microbiomes because the surface area of the phyllosphere is broad and possesses a remarkable microbial diversity (Meyer and Leveau, 2012; Vorholt, 2012; Rastogi *et al.,* 2013). All plants microbiome has several neutral and beneficial inhabitants, they also possess pathogens of plants and humans as well (Berg *et al*., 2014). A vast range of plant pathogens is well recognized to cause outbreaks of diseases in them. The interaction between the soil and the microbial diversity of the rhizosphere which have a selective subset in common has been reported (Smalla *et al*., 2001). Plant defense signaling performs a vital task in this process (Doornbos *et al*., 2012). An essential part of phyllosphere bacteria is in constant contact with the air microbiome while some fewer fraction reside within the phyllosphere (Lindow and Brandl, 2003). As a result of this fact, there is an obvious huge association and exchange between the phyllosphere, rhizosphere microbiome and neighbouring microbiome. A study conducted by Mahnert *et al*. (2015), promotes the hypothesis that indoor plants contributes significantly to the abundance and diversity of microorganisms in an indoor environment.

Fungi and bacteria are reputable colonizers of plants, but plant-associated Archaea (*Euryarchaeota, Methanobrevibacter* and *Thaumarchaeota*) have been found on the leaves of olive plant (Müller *et al*., 2015). As a result of the fact that numerous indoor pathogens are recognized as source of some health issues, (Nunes da Rocha *et al*., 2009), a greater diversity could actually hinder the colonization of these pathogens. All environmental microbes interplay with the microbiomes of house plants which also act as a bio-resource.

Beneficial effects of the phyllosphere on the indoor environment

Some studies reveal that plant-associated microbes play both beneficial and detrimental roles in the environment with the former possessing higher impacts than the latter (Berg *et al.,* 2005; Mendes *et al*., 2013).

The effect of the phyllosphere on stabilizing the indoor ecosystem

Constructed environments, such as hospitals, are more easily colonized by pathogens associated with patients (Oberauner *et al*., 2013). Consequently, a lot of patients in hospitals and particularly in intensive care units (ICUs) get hospital-acquired "nosocomial infections" that worsen their initial critical disease (Plowman, 2000). Bacteria associated with plants could serve as opposing agents against pathogens found in the microbial ecosystems (Bamidele et al. 2013, Ayeni and Afolayan, 2017). They provide stability to the ecosystem and prevent pathogen outbreak by enhancing biodiversity. Genera such as *Pseudomonas, Bacillus Streptomyces, Enterobacter, Paenibacillus, Pantoea, Paraburkholderia* and *Burkholderia* have played vital role in the suppression of pathogens (Gomez *et al.,* 2017). Acidobacteria, Actinobacteria, and Firmicutes were reported to control the invasion of *Fusarium wilt* at a continental scale (Trivedi *et al,* 2017). The activity of endosphere microbial community in suppressing take-all disease (*Gaeumannomyces graminis*) was reported by Durán *et al*. (2018),

Some plant-associated microorganism which includes: *Pseudomonas aeruginosa, Stenotrophomonas maltophilia* or *Burkholderia cepacia* may be pathogenic to humans with predispositions, they however play a significant role in maintaining a balance to the indoor ecosystem when this environment harbour abundant diversified microorganisms.

The effect of the phyllosphere on enhancing indoor biodiversity

Microbial diversity is implicated as vital for human and plant health and can be enriched by various sources of microbial release. Plants, asides animals and humans are usually a portion of indoor environments and providing sustainable source for microbial communities, thus enhancing indoor microbial diversity (Berg *et al*., 2014; Mahnert *et al.,* 2015; Brilli *et al*., 2018). Plants individually have distinct microbiomes; the productivity and health of the plant and its surrounding environment is dependent on their functional interplay. Many more evidences are rising that points that a degree of microbial abundance and diversity critically influences human health, for example, Fujimura *et al*. (2014) showed that there was a unique gut microbiome composition in mice that were exposed to dust in homes where dogs resides, these mice had protection against the challenge of airborne allegies as a result of *Lactobacillus johnsonii* enriched microbiome.

A study carried out by Hanski *et al*. (2012) confirmed the biodiversity hypothesis which states that decreased contact of people with features of the natural environmental and biodiversity may negatively influence the community of commensals in the human microbiota and likewise its immunomodulatory capacity.

The effect of the phyllosphere in degrading indoor pollutants

Viable indoor microbes released from plants have the ability to metabolize chemicals present in the built environment. Experiments carried out in laboratories proved that microorganisms in the environment microbes can degrade varieties of chemicals found in regular products in homes or furnitures, such as perfluorooctanoate (PFOA) and several other chemicals which can disrupt the endocrine, resulting in more bioavailable or bioactive chemicals and sometimes decreasing their toxicity (Kim *et* al., 2008; Blavier *et al*., 2016; Janicki *et al*., 2016; Vejdovszky *et al*., 2017). Eradication of potency of volatile formaldehyde by indoor plants has been reported (Kim *et al.* 2008)

IMPROVING THE INDOOR MICROBIOME

The use of indoor plants

A relevant source of useful microorganisms is the indoor plants which can bring a rise in microbial diversity, these useful microbes have the ability to influence a room's microbiome (Mahnert *et al.,* 2015). Contact with natural vegetation particularly in an outdoor environment is key in microbial diversity and health, however, humans cannot continuously stay outdoor, therefore microbial researches have suggested the contingency of increasing the microbiome of a room by the use of indoor plants (Mahnert *et al.,* 2015), to enhance the population of beneficial microorganism and invariably microbial diversity (Berg *et al.,* 2014).

Plants microbes have the ability to degrade human, plant and environmental toxic compounds (Bringel and Couee ´ 2015), they can also assist in the maintenance of healthy indoor air quality in an environment. Indoor plants (Orwell *et al.* 2004; Pegas *et al.* 2012) together with the microbes associated with them function synergistically to ameliorate the quality of the air (Weyens *et al.* 2015). The bringing of plants into built environments is capable of suppressing the growth of pathogenic fungi and molds which are the etiology of 'sick building' syndrome (Strauss 2009).

The use of natural ventilation

Window ventilation is known to bring an increase in the abundance of chloroplast DNA than in rooms exclusively ventilated mechanically. It has been reported that patient rooms ventilated by windows had lesser population of potentially pathogenic bacteria than in rooms ventilated mechanically confirming that natural ventilation (opening of windows) is a better design for microbial diversity (Kembel *et al.* 2012, Oberauner *et al*., 2013),).

Meadow *et al*. (2013) suggested opening of windows instead of using air conditioner, the study highlighted that air source and ventilation strategy are probably more important than the contribution of humans and their activities to the total detectable airborne microbial community.

Conflicts of Interest:

The author declare no conflicts of interest.

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