Relationship between indoor environmental quality and building envelopes covered by plants: a review of the literature

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Abstract: It is not clear whether the benefits of improving outdoor environmental conditions inherent in urban plants apply to building indoor environment when plants are integrated on building envelopes. This paper reviews published research to date to clarify whether building envelopes covered by plants have effects on indoor environmental quality, and building occupants' health and comfort. The review exercise revealed that building envelopes covered by plants can (1) improve indoor thermal and acoustic conditions (2) compromise indoor light level. Evidences addressing the impact on indoor air quality (chemical, physical, and biological pollutants) is lacking in the literature. There are no evidences in the literature addressing the impact of improved IEQ conditions, as a result of plants integrated on building envelopes, on building occupants' health and comfort. This study is relevant to creating energy efficient and sustainable buildings.

Keywords: greenery; sustainable building; health and comfort; sustainable built environment; green building; sustainable construction.

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1 Introduction

Improving indoor environmental quality (IEQ) is essential, because of its potential social, economic, and environmental benefits. Providing better indoor environment could result in improvement in building occupants' health and comfort (Wu et al., 2007). The economic benefit could even be in billions of US dollars (Fisk and Rosenfeld, 1997). However, a direct relationship that exists between indoor and outdoor environments may compromise IEQ. Major components of IEQ include indoor air quality (IAQ), thermal, acoustics, and visual/light. For IAQ, there are evidences suggesting moderate to high correlations between outdoor environmental qualities (OEQ) and IEQ exist (Li, 1994; Lee et al., 1997). Moderate to high correlations also exist between indoor and outdoor temperatures (Sakka et al., 2012). Quality of life experienced by building occupants has correlation to OEQ condition (Ohrstrom et al., 2006). Parallels can be drawn on quality of life experienced by building occupants with exposure to natural light (Leslie, 2003). Considering evidences suggesting correlation between OEQ and IEQ, efforts made to improve OEQ will have impact on IEQ. Plants seem to be viable option of improving OEQ. In terms of air quality, outdoor plants could remove hundred thousand tons of outdoor pollutants (Nowak et al., 2006; McDonald et al., 2007; Jim and Chen, 2008). The benefits could range from thousands to billions of US dollars depending on plant coverage (Nowak et al., 2006). Plants can also provide outdoor thermal improvement. This benefit will vary depending on the plants coverage area and distance away from the plants site (Wong and Yu, 2005; Chen and Wong, 2006). Plants provide pleasant outdoor environment because of their sound attenuation quality (Fang and Ling, 2003). Plants are also known to be good inhibitors of ultraviolet light radiation (UVR) exposure in outdoor environment. This is due to plants' ability to provide shade from sunlight (Gies and Mackay, 2007). Although this may be good for human outdoor condition experience, the relationship between outdoor light levels, and quality of life and energy saving benefits in indoor environment means plants integrated on building envelope may not be beneficial in this instance.

Although there are evidences supporting usage of plants as an effective method of achieving improved OEQ, it is however not clear whether improved OEQ provided by plant would be enough to improve IEQ, especially with plants being integrated on building envelope due to land limitation which is very common nowadays because of increasing human population. This study reviews published research to date to clarify whether OEQ improvement provided by building envelope covered by plants either as green roof, green wall or trees planted around building envelopes in very close proximity (like that of Bosco Verticale project in Milan with tress planted on roof tops and on balconies) could improve qualities determining better indoor environment. The effects of building covered by plants on IEQ mandates which include thermal, indoor air, acoustics, and light, are discussed in Sections 3 to 6. Indoor spatial quality (another IEQ mandate) is not discussed in this study because it is not directly relevant.

2 Methods

Search for relevant articles was done electronically via Science Direct, and 'Google Search'. Although, this review focuses mainly on peer reviewed journal papers, a few peer reviewed conference papers and a thesis judged to be very relevant to the review exercise were also considered. Books and other technical papers were not included in this review. Selected papers were searched using keywords that are related to plants, greenery and that describe effects of greenery/plants, integrated on building envelope, on OEQ and the effect improved OEQ on IEQ. Search was also done for papers that describe effects of improved IEQ, as a result of plants integrated on building envelope, on building occupants' health and comfort. Impact of indoor plants is out of scope of this review. The literature was searched to answer the following questions: can integration of plants on building envelopes improve

1 indoor: air quality, thermal, acoustics, and light conditions?

2 building occupants' health and comfort?

There was no restriction imposed on publication date. Out of more than 100 papers retrieved for review using the searching keywords, 47 papers deemed to be very relevant specifically to the above questions were selected for review. Outcome of review exercises are presented in Tables 1 to 4.

3 Effects on indoor thermal performance

3.1 Factors affecting and outcomes of plants integrated on building envelope

Indoor environment of a building covered by dense plants can provide better thermal performance than a building covered by sparse plants, while a building covered with sparse plants will provide better thermal performance than a building envelope with no plants (Niachou et al., 2001; Papadakis et al., 2001; Getter et al., 2011). Plants improve thermal behaviour and dynamics thermal characteristics of building envelope. An estimated 5.1°C indoor air temperature reduction can be achieved when envelope is covered with plants as compared to bare envelope (Kumar and Kaushik, 2005). Surface temperature reduction could range between 18°C to 30°C when building envelope is covered with plants as compared to bare envelope (Wong et al., 2007; Onmura, 2001). The ability of plants to provide solar radiation protection is a contributing factor to indoor temperature reduction benefit. Plants' solar radiation protection efficiency is a function of leaf area index (LAI). LAI is defined as half the square metres of leaf per square meter of ground. Higher plant LAI improves plant efficiency in reducing indoor air temperature (Fang, 2008; Spala et al., 2008; Tabares-Velasco and Srebric, 2012). It reduces outdoor to indoor heat (Liu, 2003; Ouldboukhitine et al., 2011), and improves energy saving performance (Wong et al., 2007). Plant moisture content, growing media (substrate) type and depth can also contribute to thermal performance superiority of building envelope covered by plants over that not covered by plants (Rezaei, 2005; Tabares-Velasco and Srebric, 2011). The higher the moisture contents of growth medium, the higher the evapotranspiration that will occur. Evapotranspiration which is a combination of water loss from soil (evaporation) and plants (transpiration) is a major contributing factor to heat fluxes reduction through building enclosure covered by plants (Rezaei, 2005). Depending on plant canopy coverage, evidences have shown that wet green roof samples could produce 12% to 25% incoming heat flux reduction performance than dry green roof samples (Tabares-Velasco and Srebric, 2011; Wong et al., 2003a). Thicker soil layer will further increase thermal insulation; reduce demand for both heating and cooling (Wong et al., 2003b; Sailor, 2008; Permpituck and Namprakai, 2012). The benefits will also vary depending on the quality of the substrate. Burned sludge is an example of quality substrate because of its excellent porosity and water holding capacity (Lin and Lin, 2011). Seasons can also influence plants performance. Temperature reduction benefit provided by plants integrated on building envelope will be maximised during summer season. Getter et al. (2011) observed that green roof temperatures were consistently 5°C lower than corresponding gravel roof temperature in autumn season. In summer, the temperature differences reach as much as 20°C. They observed that plant covered roof was observed to reduce heat flux through the building envelope by 167% and 13% during summer and winter respectively. Plant integrated directly on building envelope (e.g., directly on wall or roof) will reduce heat flux from outdoor to indoor environment during summer, thus saving energy consumption due to cooling loads. It (plant integrated directly on building envelope) will reduce heat flux from indoor to outdoor environment during winter season, thus saving energy consumption due to heating loads (Getter et al., 2011).

Orientation will also contribute to impacts of plant application. Possibilities of plants reducing undesirable effects of high temperature will vary depending on wall orientation. According to Granados et al. (1999), plants effectiveness in reducing solar radiation incidence on wall, improving indoor environment thermal condition and reducing peak power consumption will be more pronounced on the south façade. It is important to note that temperature and energy benefits derived from integrating plants on building envelope will vary depending on insulation quality of the building. A well-insulated building was reported to provide 2% energy savings versus 37–48% energy savings observed for non-insulated buildings in a study conducted in Athens, Greece (Niachou et al., 2001). This suggests that application of vegetation in old buildings with poor insulation materials due to codes at that time may be more beneficial than new buildings having stringent laws on insulation materials (Castleton et al., 2010). Table 1 shows results of the literature review done in order to gather evidences supporting:

1 indoor thermal condition outcomes when building is covered by plants

2 factors affecting indoor thermal condition caused by plants integrated on building envelope.

This was done to understand current knowledge with regards to the question: can plants integrated on building envelopes improve indoor thermal condition and subsequently improve building occupants' health and comfort as a result of improved indoor thermal condition? Such a review exercise also helps to identify knowledge gaps with regards to the questions.

Table 1 Factors affecting changes in indoor thermal condition caused by plants integrated on building envelope and outcomes of such integration*

References	*Method(s) adopted*	*Country context*	*Type of greenery studied*	*Direct implications on indoor thermal condition examined*	*Indoor thermal condition outcomes when building is covered by plants*					*Factors affecting changes in indoor thermal condition caused by plants integrated on building envelope*					
					Heat transfer and/or temperature reduction	*Humidity increase*	*Energy savings*	*Temperature and humidity fluctuation reduction*	*Wind speed reduction*	*Evapotranspiration effects*	*Substrate effects*	*Canyon effects*	*Orientation effects*	*LAI effects and/or plant coverage*	*Building insulation properties*
Tabares-Velasco and Srebric (2012)	M	Not applicable	R	Yes	+		∞			O	O				
Niachou et al. (2001)	ME	Greece	R	Yes	+		+							O	O
Zinzi and Agnoli (2011)	M	Not applicable	S	Yes	+		+			O					
Wong et al. (2003a)	F	Singapore	R	Yes	+	×	∞				O			O	
Onmura et al. (2001)	MFE	Japan	R	Yes	+		+			O					
Papadakis et al. (2001)	E	Greece	S	Yes	+	×	+		+	O				O	
Jim and He (2011)	ME	Hong Kong, China	W	Yes	+		∞						O	O	
Ouldboukhitine et al. (2011)	ME	France applicable	R	Yes	+	+	+			O				O	
Fang (2008)	E	Taiwan	R	Yes	+									O	
Eumorfopoulou and Kontoleon (2009)	E	Greece	W	Yes	+		∞			O					

Notes: M: mathematical modelling method; ME: mathematical modelling and experimental methods; F: Field study method; E: experimental method; MFE: mathematical modelling, field study and experimental methods; S_m: simulation method; F S_m: field study and simulation methods; R: green roof; W: green wall; RW: green roof and wall; S: stand -alone plants (e.g. tree and/or forest); +: outcome observed; ×: no consistent plant influence observed; ∞: plants influence inferred not measured/calculated directly; O: Factor effect observed.

*Effects of improved indoor thermal condition, caused by building envelopes covered by plants, on building occupants' health and comfort have received little or no attention in the literature.

Table 1 Factors affecting changes in indoor thermal condition caused by plants integrated on building envelope and outcomes of such integration* (continued)

References	*Method(s) adopted*	*Country context*	*Type of greenery studied*	*Direct implications on indoor thermal condition examined*	*Indoor thermal condition outcomes when building is covered by plants*					*Factors affecting changes in indoor thermal condition caused by plants integrated on building envelope*					
					Heat transfer and/or temperature reduction	*Humidity increase*	*Energy savings*	*Temperature and humidity fluctuation reduction*	*Wind speed reduction*	*Evapotranspiration effects*	*Substrate effects*	*Canyon effects*	*Orientation effects*	*LAI effects and/or plant coverage*	*Building insulation properties*
Tabares-Velasco and Srebric (2011)	E	USA	R	Yes	+		∞			O	O			O	
Teemusk and Mander (2009)	F	Estonia	R	Yes	+			+			O			O	
Stec et al. (2005)	ME	Netherland	W	Yes	+		+							O	
Kumar and Kaushik (2004)	M	India	R	Yes	+		+	+		O				O	
Maclvor and Lundholm (2011)	F	Canada	R	Yes	+		+								
Suscaet al. (2011)	F	USA	R	Yes	+		∞								
Getter et al. (2011)	F	USA	R	Yes	+			+							
Ip et al. (2010)	ME	UK	W	Yes	+			+		∞				O	
Wong et al. (2009)	S_m	Singapore	W	Yes	+		+							O	
Alexandri and Jones (2008)	M	Multi-countries	RW	No	+		+		+			O	O	O	
Teemusk and Mander (2010)	F	Estonia	R	Yes	+			+			O				

Notes: M: mathematical modelling method; ME: mathematical modelling and experimental methods; F: Field study method; E: experimental method; MFE: mathematical modelling, field study and experimental methods; S_m: simulation method; F S_m: field study and simulation methods; R: green roof; W: green wall; RW: green roof and wall; S: stand -alone plants (e.g. tree and/or forest); +: outcome observed; ×: no consistent plant influence observed; ∞: plants influence inferred not measured/calculated directly; O: Factor effect observed.
*Effects of improved indoor thermal condition, caused by building envelopes covered by plants, on building occupants' health and comfort have received little or no attention in the literature.

Table 1 Factors affecting changes in indoor thermal condition caused by plants integrated on building envelope and outcomes of such integration* (continued)

References	*Method(s) adopted*	*Country context*	*Type of greenery studied*	*Direct implications on indoor thermal condition examined*	*Indoor thermal condition outcomes when building is covered by plants*					*Factors affecting changes in indoor thermal condition caused by plants integrated on building envelope*					
					Heat transfer and/or temperature reduction	*Humidity increase*	*Energy savings*	*Temperature and humidity fluctuation reduction*	*Wind speed reduction*	*Evapotranspiration effects*	*Substrate effects*	*Canyon effects*	*Orientation effects*	*LAI effects and/or plant coverage*	*Building insulation properties*
Kontoleon and Eumorfopoulou (2010)	M	Greece	W	Yes	+		+						O	O	
Wong et al. (2010a)	E	Singapore	W	Yes	+			+			O			∞	∞
Cheng et al. (2010)	E	Hong Kong, China	W	Yes	+			+						O	
Lin and Lin (2011)	E	Taiwan	R	Yes	+						O			O	
Wong et al. (2003b)	S_m	Singapore	R	Yes	+		+				O				
Permpituck and Namprakai (2012)	F S_m	Greece	R	Yes	+		+				O				
Sailor (2008)	M	USA	R	Yes	+		+			O	O			O	
Perini et al. (2011)	E	Netherland	W	Yes	+		+		+					O	O
Feng et al. (2010)	ME	China	R	Yes	+		+	∞	∞	O	O			O	

Notes: M: mathematical modelling method; ME: mathematical modelling and experimental methods; F: Field study method; E: experimental method; MFE: mathematical modelling, field study and experimental methods; S_m: simulation method; F S_m: field study and simulation methods; R: green roof; W: green wall; RW: green roof and wall; S: stand -alone plants (e.g. tree and/or forest); +: outcome observed; ×: no consistent plant influence observed; ∞: plants influence inferred not measured/calculated directly; O: Factor effect observed.

*Effects of improved indoor thermal condition, caused by building envelopes covered by plants, on building occupants' health and comfort have received little or no attention in the literature.

3.2 Knowledge gap

As evident in Table 1, there are numerous studies supporting the importance of plant-covered building envelope in improving building indoor thermal performance. Though one may speculate that this temperature reduction would lead to improvement in building occupants' health and comfort, there is insufficient evidence in the literature to support this speculation.

4 Effects on IAQ performance

4.1 Factors affecting and outcomes of plants integrated on building envelope

The focus of this section is on the impact of outdoor plants integrated on building envelopes on reducing outdoor to indoor transport of pollutants. Indoor pollutants, which may be chemical, physical, and biological, can largely be attributed to polluted outdoor environment (Weisel et al., 2005; Weschler, 2000). Measures necessary to mitigate migration of outdoor pollutants to indoor environment is essential. Studies have shown that plants can serve as a biological filters removing large amount of airborne pollutants due to their large leaf area relative to the ground on which they stand and the physical properties of their surfaces (Rowe, 2011). Airborne pollutants are captured through deposition on plant leaf and bark surfaces. Plants may reduce outdoor air pollutants concentration by wet (precipitation, e.g., rain and snow), occult (wind-driven cloud water), or dry (non-precipitation) depositions. Local atmospheric chemistry, meteorology, canopy characteristics, leaf microstructure and cell physiology are known to affect dry deposition rate of air pollutants (Beckett et al., 2000). Openness of plant stomata increases dry deposition process of gaseous pollutants (Matsuda et al., 2006). Increasing plant canopy can be effective in removing large amount of pollutants that may be generated in urban environments (Yang et al., 2008). Plants' air pollutant removal efficiency will increase with large and continuous trees, and with more air pollutants (Jim and Chen, 2008). It is evident that building envelopes covered by plants can serve filter like object that can reduce concentration of outdoor pollutants around building envelopes. This is essential in reducing load and stress on mechanical ventilation systems components, cracks (leakages) and openings. Such phenomenon can potentially improve IAQ. Table 2 shows results of the literature review done in order to gather evidences supporting:

1 indoor air condition outcomes when building is covered by plants

2 factors affecting indoor air condition caused by plants integrated on building envelope.

This was done to understand current knowledge with regards to the question: can plants integrated on building envelopes improve indoor condition and subsequently improve building occupants' health and comfort as a result of improved indoor air condition? This exercise can also help to identify the niche within this area.

Table 2 Factors affecting changes in indoor air condition caused by plants integrated on building envelope and outcomes of such integration*

References	*Method adopted*	*Country context*	*Type of greenery studied*	*Direct implications on IAQ examined***	*Factors affecting changes in indoor air condition caused by plants integrated on building envelope*				
					Plants coverage effects	*Deposition velocity effects*	*Outdoor pollutants concentration effects*	*Stomata effects*	*Leaf structure and/or plant species effects*
Pal et al. (2002)	E	India	S	No				O	O
Sternberg et al. (2010)	F	UK	W	No	O		O		
Yang et al. (2008)	M	USA	R	No	O		O		
Hwang et al. (2011)	E	Korea	S	No		O			O
Wang et al. (2006)	F	China	S	No	O	O			O

Notes: M: mathematical modelling method; F: field study method; E: experimental method; R: green roof; W: green wall; S: stand-alone plants (e.g., tree); O: factor effect observed.
*Effects of improved indoor air quality, caused by building envelopes covered by plants, on building occupants' health and comfort have received little or no attention in the literature.
**The author could not find any study examining the direct impacts of building envelope covered by plants on reduction of outdoor to indoor transport of pollutants. All studies found focused on outdoor pollution removal. Reduction of outdoor pollution, caused by building envelopes covered by plants, is observed in all reviewed papers.

4.2 Knowledge gap

Studies addressing integration of plants on building envelopes show the importance of this integration on pollutants reduction around building envelope. One may speculate that outdoor pollution reduction caused as a result of the integration would lead to reduction of indoor air pollution, due to possible reduction of outdoor to indoor transport of pollutants, and consequently, improve building occupants' health and comfort. As evident in Table 2, there is a dearth of evidence to justify this speculation. More research efforts to address these knowledge gaps are needed.

5 Effects on indoor acoustic performance

5.1 Factors affecting and outcomes of plants integrated on building envelope

Sound level in a space is referred to as acoustic condition while state of contentment with acoustic condition defines acoustic comfort. Sound becomes noise if it is causing annoyance. Noise can cause distraction, thus providing less ideal living and working and learning environments. Sources of sound (noise) may be from outdoor or indoor. Since this paper is addressing how building envelope covered by plants could be used to reduce impact of outdoor environment on indoor environment, the focus is on outdoor sources. Examples of outdoor sources include airfields, highways, factories, railways, construction activities, etc. Incorporating appropriate sound control measures is essential in reducing outdoor to indoor transport of sound. From an economic perspective, seeking to apply a single design approach to achieve multiple design objectives is essential. Example of such an approach is integration of plants on building envelope. Plants reduce perceived sound level due to absorption, diffraction, and reflection of sound (Pal et al., 2000). Structure, materials and dimension of envelope, moisture content of substrate and plant species are some of the major factors that impact plant acoustic performance (Wong et al., 2010b). Table 3 shows results of literature review done in order to gather evidences supporting:

1 indoor acoustic condition outcomes when a building is covered by plants

2 factors affecting indoor acoustic condition caused by plants integrated on building envelope.

This was done to understand current knowledge with regards to the question: can plants integrated on building envelopes improve acoustic condition and subsequently improve building occupants' health and comfort as a result of improved indoor acoustic condition? This investigation also aids in determining knowledge gaps with regards to the question.

5.2 Knowledge gaps

There are very limited studies addressing the importance of plants integrated on building envelope, on sound attenuation. However, some available studies suggest that plants integrated on building envelope could reduce sound levels and improve perceived sound reduction. As evident in Table 3, more research with focus on buildings covered by plants are needed to be able to understand whether sound level attenuation provided by plants integrated on building envelope could lead to lower indoor sound level and possibly improve occupant health and comfort.

Table 3 Factors affecting changes in indoor acoustic condition caused by plants integrated on building envelope and outcomes of such integration*

References	*Method adopted*	*Country context*	*Type of greenery studied*	*Direct implications on indoor acoustic condition examined***	*Indoor acoustic condition outcomes when building is covered by plants*		*Factors affecting changes in indoor acoustic condition caused by plants integrated on building envelope*		
					Outdoor to indoor transport of noise level and/or indoor noise level reduction	*Human health and comfort-specifically on indoor exposure*	*Plants coverage effects*	*Sound frequency effects*	*Substrate effects*
Yang et al. (2012)	ES_m	UK	R	No				O	O
Wong et al. (2010b)	E	Singapore	W	Yes	+		O	O	O
van Renterghem and Botteldooren (2011)	M	Belgium	R	No			O	O	O
Gidlof-Gunnarsson and Ohrstrom (2007)	Q	Sweden	S	Yes		+			

Notes: M: mathematical modelling method; FE: field study and experimental methods; ES_m = experimental and simulation methods; F: field study method; E: experimental method; Q: questionnaire; R: green roof; W: green wall; S: stand-alone plants (e.g., tree); +: outcome observed; O: Factor effect observed
*Effects of improved indoor acoustic condition, caused by building envelopes covered by plants, on building occupants' health and comfort have received little attention in the literature.
**There are very little studies examining the direct impacts of building envelope covered by plants on reduction of outdoor to indoor transport of sound. Reduction of outdoor sound level, caused by building envelopes covered by plants, is observed in all reviewed papers.

6 Effects on indoor visual performance

6.1 Factors affecting and outcomes of plants integrated on building envelope

Indoor light level due to daylight penetration is the focus of this section. Benefits of daylighting indoor environment include improved building life-cycle cost, increased user productivity, reduced greenhouse gas emissions (provided solar heat is prevented from penetrating indoors), and reduced operating costs (Leslie, 2003). Daylighting indoor environment is coupled with precaution of holistic consideration for reducing heat transfer into indoor environment, avoiding glare problem, and increasing luminance level and increasing daylight depth of penetration, thus, reducing the need for artificial light as much as possible. Can integration of plants on building envelope reduce heat transfer from outdoor to indoor? The answer is in the affirmative based on understanding from Section 3 of this paper. The shading benefit provided by plant reduces sensible and latent cooling loads. However, it also reduces daylight levels penetrating into the indoor environment (Akbari et al., 1997), thereby increasing the need for artificial lighting that will incur more energy penalties. Due to comfort, health, and wellbeing associated with viewing of plants, building occupants may be compelled to open internal blinds, allowing shaded light levels, subsequently reducing the use of artificial lighting to some extent. Table 4 shows the results of the literature review done in order to gather evidences supporting:

1 indoor light (visual) condition outcomes when building is covered by plants

2 factors affecting indoor light condition caused by plants integrated on building envelopes.

This was done to understand current knowledge with regards to the question: can plants integrated on building envelopes improve light condition and subsequently improve building occupants' health and comfort as a result of improved indoor light condition? This analysis will also further reveal knowledge gaps within the specified realm.

6.2 Knowledge gaps

Unfortunately, very little has been done to address the possible impact of plants integrated on building envelope on glare and daylight penetration into the indoor environment (see Table 4). Most studies focus on heat transfer reduction, shading benefits, energy savings, cooling effects, humidity effects, insulation effects, temperature fluctuation reduction, importance of soil/substrates, etc. The question: 'can vegetation covered building envelopes improve indoor visual performance and possibly improve occupants' health' remains unanswered.

Table 4 Factors affecting changes in indoor light condition caused by plants integrated on building envelope and outcomes of such integration*

References	*Method adopted*	*Country Context*	*Type of greenery studied*	*Direct implication on IEQ examined***	*Plants coverage effects*
Papadakis et al. (2001)	E	Greece	S	No	+
Wong et al. (2009)	S_m	Singapore	W	No	+
Gies et al. (2007)	F	Australia	S	No	+
Gies and Mackay (2007)	F	New Zealand	S	No	+
Ip et al. (2010)	ME	UK	W	No	+
Alexandri and Jones (2008)	M	Multi-countries	RW	No	+
Wong et al. (2003b)	S_m	Singapore	R	No	+
Perini et al. (2011)	E	Netherland	W	No	+

Notes: M: mathematical modelling method; Sm= simulation methods; ESm: experimental and simulation methods; S: stand-alone plants (e.g. trees); R: green roof; W: green wall; RW: green roof and wall; +: plants influence observed.
*Effects of indoor light condition, caused by building envelopes covered by plants, on building occupants' health and comfort have received little attention in the literature.
**Studies examining the direct impacts of building envelope covered by plants on indoor light condition is lacking in the literature. Reduction of outdoor light level, caused by building envelopes covered by plants, is observed in all reviewed papers.

7 Conclusions and future directions of research

Environmental life cycle assessment study by Kosareo and Ries (2007) has shown the importance of integrating plants on building envelope towards achieving sustainable built environment. However, as evident in Table 1, it is imperative that more research is conducted to understand the importance of building envelope integrated with plants on IEQ, and human health and comfort. Most research efforts addressing the impacts of the relationship between buildings covered by plants and its IEQ performance focus on indoor thermal performance. Even for thermal performance studies, implications of the relationship on human health and comfort have received little or no attention. The following suggested future research studies may be conducted objectively and subjectively via field study, chamber/laboratory study, and or mathematical modelling/simulation approach. In addition to the future direction of research addressed from Section 7.1 to 7.4, interrelationships among these IEQ conditions should also be given due consideration because benefits derived in the attempt of using plants to cover building envelopes to improve one of the conditions may cause efficiencies in one or more of the other IEQ conditions. Since buildings are designed primarily for humans, building occupants' limits of acceptability which is a function of their physiology, psychology, social, and economics (Hartkopf et al. 1986), should be addressed when researching integration of plants on building envelopes.

Terms of evaluation which include suitability, durability/reliability, and flexibility of integrating plants on building envelope should also be explored. Integration of plants on building envelope should not compromise IEQ conditions when a building is delivered for occupancy (suitability). Maintenance and operations needed to ensure durability/reliability of IEQ performance provided by plants integrated on buildings envelope should not be overlooked. At a point in time during the life cycle of a building, there may be need to retrofit or make changes to buildings. Thus, flexibility in making changes to integration between plants and building envelopes is extremely essential.

7.1 Indoor thermal performance

Numerous studies have been conducted on the impact of building envelope covered by thermal condition. However, studies documenting the influence of building envelope covered by plants on building occupants' perceived thermal comfort, and experienced sick building syndrome (SBS) symptoms are lacking. When addressing these issues, possible impact of one or more of the following should be given consideration: importance of foliage in solar protection, temperature and humidity fluctuation effects, importance of soil/substrate, wind speed reduction effects, seasonal effects on greenery performance, solar orientation effects, shading benefit effects, plant coverage ratio effects, climatic region effects, canyon effects, façade orientation effects, and intensive and extensive green roof effects.

7.2 IAQ performance

Within this rigorous scrutiny of literature, no paper was specifically found addressing the impact of green roof, green wall and trees planted around building envelopes in very close proximity on IAQ. Very little is known with regards to indoor air pollution reduction and reduction of outdoor to indoor transport of pollutants. Studies that clearly address the knowledge gaps will be essential. Possible effects of a building envelope covered by plants could have on building occupants' perceived IAQ and experienced sick building symptoms should be studied. When addressing these issues, possible impact of one or more of the following should be given consideration: intensive and extensive plants covered building envelope effects, percentage of plant coverage, plant species, importance of higher dose of outdoor air pollutants, dry/wet/occult deposition effects, seasonal effects, canopy characteristics, leaf microstructure and cell physiology, stomata and non-stomata effects, and tree health.

7.3 Indoor acoustic performance

Very little is known with regard to impact of building envelope covered by plants on indoor acoustic level reduction and reduction of outdoor to indoor sound transmission. More studies are still needed in this area. Possible effects of green roof, green wall and trees planted around building envelopes in very close proximity could have on building occupants' perceived acoustic comfort and experienced sick building symptoms are receiving very little attention. When addressing these issues, possible impact of one or more of the following should be given consideration: intensive and extensive green roof effects, percentage of plant coverage, plant species, sound frequency effects, canopy characteristics, tree health, sound source distance to greenery building envelope, plants screen effects, and substrate effects.

7.4 Indoor visual performance

There is a lack of studies done on impact of green roof, green wall and trees planted around building envelopes in very close proximity on glare effects and daylight depth of penetration. Most studies focus on benefits arising from viewing green areas of greenery on health and restoration. Impact of plants integrated on building envelope could have on indoor light condition is still an area yet to be explored. Impact of light levels on occupants' perceived visual comfort and experienced sick building symptoms are yet to be studied. When addressing these issues, possible impact of one or more of the following should be given consideration: considered canopy characteristics, sound source distance to greenery building envelope, and vegetation screen effects.

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