Trees on buildings: A design framework

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Trees on buildings: A design framework

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ABSTRACT

Although interest in implementing trees on buildings has increased over the last few years, there is limited literature and policies to guide design and implementation. This lack of evidence and guidelines hinders the implementation and increases the risk of failure and maintenance costs. This study seeks to address this by investigating the design requirements of trees on buildings based on the best practice experience of worldwide experts using survey and interview techniques. This study is novel in that it introduces a complete design framework for trees on buildings that can be used to enhance future designs and implementation. The design framework consists of four stages: preparation, critical analysis and studies, techniques and design elements, and construction and maintenance plans. This design framework serves to guide designers, developers, and policy-makers to make better decisions regarding trees on buildings. This paper also highlights areas where existing policies and literature need to be improved to further enhance the design framework, broaden the knowledge regarding trees on buildings, and reduce the challenges to their implementation.

1. Introduction

Green infrastructure technologies have facilitated the implementation of living green elements on buildings, including various types of green roofs. Different terms are used in the literature to identify these various types, such as extensive and intensive green roofs, roof gardens (or rooftop gardens), and sky gardens [1,2]. Plant types, soil depth, location, and design arrangements are the main parameters to distinguish these different types. Extensive green roofs usually refer to green spaces on the roof with shallow substrate and low canopy vegetation (e.g., grasses), while intensive green roofs have moderate to deep substrates with more vegetation types, including small trees [3,4]. Roof gardens and sky gardens are similar to intensive green roofs, but they might include large trees and their design arrangements and components are similar to typical gardens on the ground level [5,6]. The difference between roof gardens and sky gardens is that the former is solely implemented on building roofs, while the latter refers to any garden arrangements on built structures, such as roofs, podiums, and balconies [7]. As trees can be included in all the above green roof settings, except the extensive green roofs, this study uses the term 'trees on buildings' as it can apply to all these settings.

Trees on buildings significantly increase the performance of the green roof settings, by reducing air pollution [8], improving biodiversity [9,10], improving thermal comfort, mitigating urban heat islands [6,11], providing shade and enhancing water balance [12,13]. The challenges of green roof settings with trees include a more intensive design process, increased building structural load capacity, costs, and services compared to those without trees. Trees, in particular, require additional consideration through design, construction, and maintenance to mitigate risks such as tree health and structural stability [5,14].

Trees on buildings are most commonly implemented on podiums and at the highest level of a building, and are therefore subject to extreme environmental conditions, such as wind and sun [15]. These conditions require multidisciplinary expertise throughout the design and construction phases of the project to mitigate risk and ensure success [16]. Green infrastructure studies, mainly concerning green roofs, often do not include trees due to their complicated requirements and numerous risks to buildings [5,15]. The existing literature regarding trees on buildings is limited and focused on implementation challenges and opportunities [7], wind loads [2,15], tree species composition and selection [5,14], and energy and thermal performance [17]. In addition, there is a lack of knowledge regarding their policies, design processes, implementation, and maintenance requirements [5,17]. For these reasons, this study focuses on understanding the design barriers of trees on buildings and providing an essential design framework to address those issues. This framework could be used as an educational reference by

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designers, developers, researchers, and policymakers, yielding better-designed and implemented trees on buildings with less risk and reduced maintenance requirements.

2. Literature and policy review

2.1. Design considerations

The climatic conditions on the upper levels of buildings where trees are implemented are harsher than ground level within the same context. The illumination intensity level could increase up to 3300 lux with an increase in the temperature of about 6 °C, wind velocity of about 0.6 m/s, and a reduction in relative humidity of about 5% [18]. In addition, planting trees in confined locations with limited soil volumes and access to sunlight, rainfall, and nutrients causes changes in their structural and morphological characteristics, including the lower canopy vegetation planted under the trees [19]. These changes could considerably affect the health and success of the plants [19,20]. Furthermore, based on the building design and the surrounding buildings, there is a risk of establishing wind tunnels and uplifting forces, which might cause additional risk to the stability of the trees [5] and considerable risk to the building structural elements [21]. Therefore, it is essential to consider all the environmental changes based on the design and location of the green roof elements, specifically if they include trees, to protect the plants from these harsh conditions [22].

Trees on buildings are mainly planted in planters [5,14], and therefore, the planter size and its characteristics have a substantial role in tree success. Each tree species needs different requirements, specifically for the soil volume. For instance, woody trees need a soil depth of up to 60 cm [5], while palms need deeper soil [23]. Although trees could adapt to the available soil volume, limited soil could impact their growth profile and place risk on their success [21,24]. Therefore, the planter design must consider this variation between the selected trees and their needs to allocate the required soil volume for each species. In addition, as trees grow vertically and horizontally, the planter location needs to be carefully assessed to ensure the planter location is suitable for the trees in their maturity stage [25]. Simultaneously, trees are required regular maintenance and size to reduce the risk of failure and increase safety [23], which also need to be considered during the design and operation stages.

Trees vary considerably in shape and size. Even the same tree species could have different characteristics if planted in different environmental conditions [26]. In addition, the form of trees and their leaf characteristics greatly influence the microclimate [27], including shade, temperature, humidity, and wind velocity. This new microclimate could change following the growth of the trees, which may positively or negatively affect both the low canopy plants, which are planted under the trees, and nearby trees, increasing the complexity of tree and plant choices for implementation on buildings. Therefore, the existing green roof standards and policies recommend selecting small trees with a low growth rate and limited canopy to overcome these challenges [28–30]. However, interest has increased towards adopting tall feature trees with wide canopies for their higher positive impact on the environment and various positive impacts on buildings and their users [5,31], which needs deeper consideration and assessment during the design process and more actions in the policies to facilitate their implementation [5].

2.2. Policy review

A review of the Australian policies relevant to trees on buildings was conducted to contextualise the study which received a majority of Australian participants (43%). In general, the policies mostly focused on green roofs [32] with a limited focus on the implementation of trees on buildings in Brisbane [33] and Melbourne [34]. Brisbane policies were introduced in 2007 and have undergone a few updates, while Melbourne policies applied in 2014 mostly depend on The Development and Construction Society (FLL)-Green Roof Guidelines, particularly for tree requirements [35]. Melbourne also developed the Green Factor tool to help designers improve their buildings to become environmentally friendly [36]. Both of these cities focused on considering tree loads, as they required (based on the policies) at least 1 m of soil depth and inclusion of anchorage systems for the trees. In addition, there is a focus on selecting the appropriate tree species by including a professional advisor (e.g., a horticulturist or registered landscape architect) in the selection process to increase the success and an arborist to supervise maintenance during the operational stage of the building [33,34]. Melbourne's policies provide general guidance on the planter design and the soil requirements, focused on providing planters with enough soil volume suitable for the tree root growth. Brisbane's policies were more detailed and included stricter planter design and soil requirements including advanced calculations for measuring the required soil volume based on the maturity stage of the selected tree species [33]. In addition, water sourcing and irrigation plans, planting schemes, structural design reports, fire safety certification, and maintenance programs are required in Brisbane for development approvals [19].

2.3. Summary

The literature and policies mentioned in the above sections provide a good basis for the required steps and challenges requiring consideration when implementing trees on buildings. However, some challenges still need to be considered to increase design and implementation success, as evidenced by a lack of literature and policies regarding trees on buildings. Abuseif, Dupre [7] ranked the challenges of the implementation of trees on buildings, and they stated that the quality of the design is the primary challenge, as poor designs are the main reason for the failure of trees on buildings and aborting the implementation of trees during the construction process [5,7,14]. Therefore, there is a need to provide a systematic design approach that incorporates the various tree implementation requirements, climatic conditions, location, design, implementation techniques, and policies. This systematic design approach must consider site-specific requirements and policies, which could be in the form of a design framework and could be applicable to be used worldwide to provide successful designs for trees on buildings. The following section presents the adopted methods to provide insight into the required systematic design approach as the main focus of this study.

3. Methodology

The previous literature review provided the state of the art regarding trees on buildings and the inherent research gaps regarding their implementation. This knowledge was then used to develop a research design framework using a combination of qualitative and quantitative approaches organised into a three-step process. The first step included the design of the study and the investigation framework. Secondly, two data sets were collected, including a survey and follow-up semi-structured interviews. The last step concerned the analysis of the data and the reporting of results.

3.1. Study design

Due to the lack of literature concerning trees on buildings, the research was expanded to include similar areas of design, such as green roofs, roof gardens, and sky gardens, to identify possible design processes and guidelines for trees on buildings. The results from the literature review were used to design and categorise the research questions for the survey and interviews as follows:

- The survey was designed to explore trees on buildings from the experts' point of view. An expert in this study is defined as a person who has experience designing, constructing, maintaining, or regulating trees on buildings. The first section of the survey included

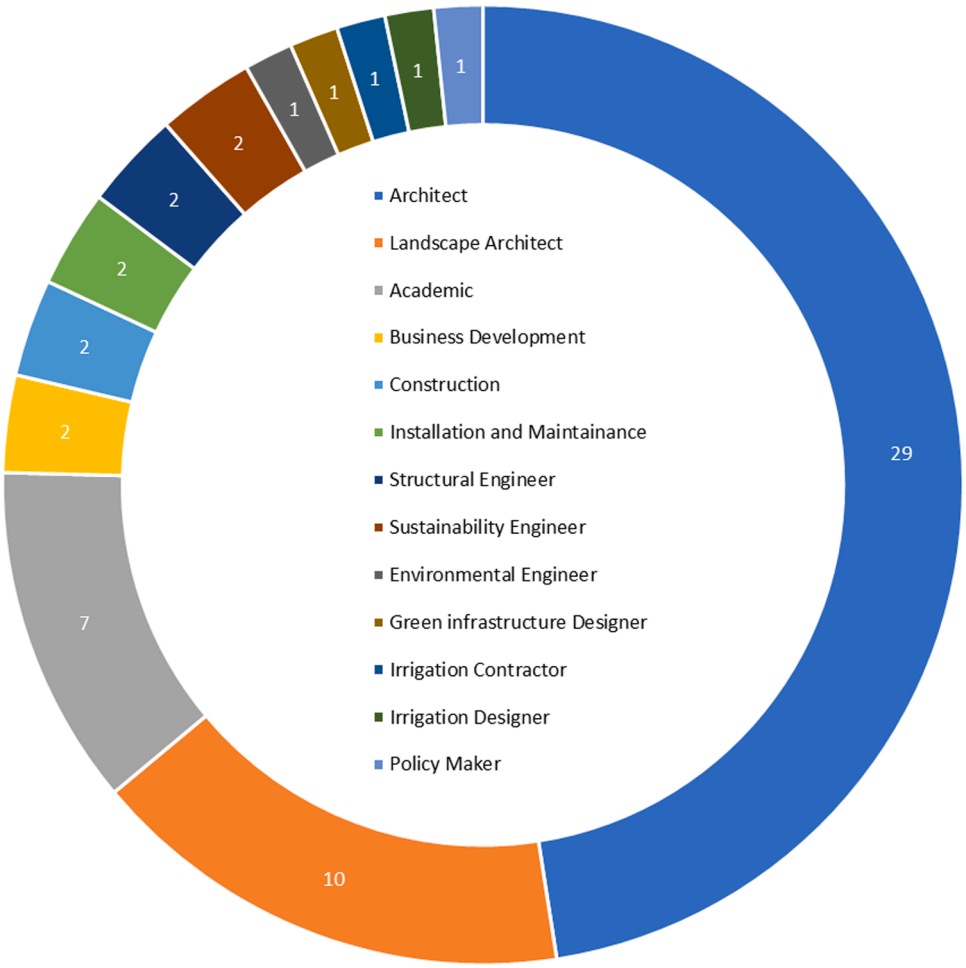

Fig. 1. Expert professional background and the number of representatives in the survey.

close-ended questions concerning the background of the experts (discipline, geographic location, role in the design and implementation process). The second section of the survey consisted of open-ended questions focusing on the design elements and the process of preparation, design, and construction of trees on buildings. It also investigated barriers, existing policies, current techniques, risks, areas of improvement and required knowledge (see full questionnaire in the appendix).

- Follow-up semi-structured interviews were conducted with those experts who expressed interest through the survey in providing more information. The aim was to expand upon the themes presented in the survey questions in richer detail.

3.2. Data collection

The survey was conducted using Google Forms. An identical survey was created using Microsoft Forms for dissemination in countries where Google Forms is restricted, specifically in China. The survey was promoted through the authors' social media, including Facebook, LinkedIn, ResearchGate, and Academia. Expert participants were also identified by a web search of projects that implemented trees on buildings and directly emailing their designers and developers. The survey remained open for four months (March 4 to July 4, 2021) and was completed by 61 experts from various backgrounds (Fig. 1) and locations worldwide, with an emphasis on Australian experts (43%) (Fig. 2), due to the origin and professional background of the authors.

Fourteen experts participated in the semi-structured interviews (64% of the twenty-two experts invited). The average time of the interviews was 34 min. The interviewees were 25% landscape architects, with the remaining 75% from diverse backgrounds, including developers, installers, maintenance experts, plant health experts, agricultural engineers, policymakers, and fire engineers. No architects or academics participated in the interviews.

3.3. Data analysis protocol

NVivo 12 was selected for this study, as it is commonly used to analyse unstructured written data [37]. It helps index the text inside the documents, search for words and phrases in the data, and link them to themes, contexts, and categories [38]. The survey data was exported to MS Excel from Google Forms and Microsoft Forms. The recorded interviews were automatically transcribed using Otter.ai and then edited manually for accuracy. The transcripts from the surveys and interviews were analysed to identify the main themes using NVivo Word Frequency query and Word Tree. The data were coded, categorised, and analysed based on the identified themes presented in Table 1. Participant responses were given unique identifiers: S-number (S01-S61) for survey responses and I-number (I01-I14) for interview responses. The research questions and relevant theoretical concepts guided the initial coding process. The coded themes emphasised the emerging relationships between the analysed data, which were used then to categorise the results section.

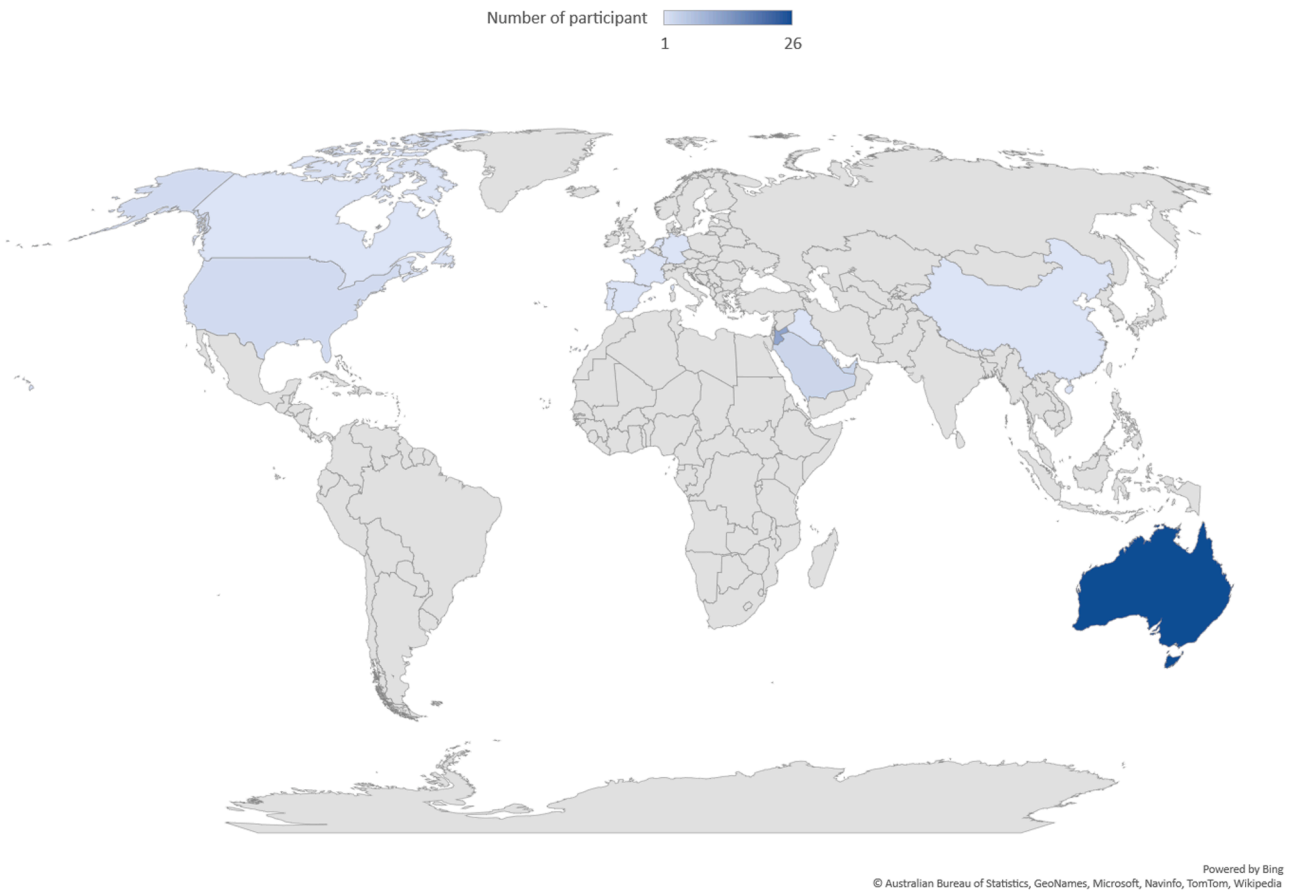

Fig. 2. The geographic locations of the survey and interview participants.

4. Results

4.1. Design preparation for trees on buildings

4.1.1. Background and awareness

Most of the participants (98%) supported the view that green roof settings, including trees, are essential elements of buildings, as they benefit building performance, developers, end-users, and the environment. Overall, participants noted that trees on buildings enhance building aesthetics, increase building value, enhance the health and lifestyle of end-users, the microclimate, and mitigate global warming. A landscape architect (I08) even specified, "*they should not be considered a luxury; they should be considered a standard that we do on every single building*". However, incorporating trees on buildings requires essential design details to be considered, particularly soil volume, tree type, root, and wind loading. These requirements increase the construction and building running costs and maintenance. Usually, an unawareness of these requirements resulted in "*excluding the implementation of the trees in many projects*" (I14), as the initial and running costs, and the maintenance requirements are not allocated within the project budget. Consequently, *"a better understanding of the long-term impacts of trees near buildings, so you can argue against the initial increase in building cost"* (S01) is essential to convince developers to adopt trees on buildings. A few participants (10%) believe that educational institutions and city councils should increase the knowledge of trees on buildings amongst the general public. For instance, *"this issue needs more work on people, education and flexibility in adapting new ideas and change, especially if the benefits of this change are considered significant"* (S18). Regarding implementation risk, S28 stated, *"Anything in building construction could be risky unless it is done properly"*. Many participants (52%) agreed that all the associated risks could be easily mitigated if trees on buildings were designed and constructed correctly.

4.1.2. Design team

The existence of trees and the challenging microclimate on buildings increases the complexity of the design process of green roof settings. All participants emphasised the importance of the architect and landscape architect roles in the design stage. However, the challenges are substantial and more input from other experts is needed: "*it is not just the landscape architect telling an architect [that] they need to put trees on a building. It is about the architect, engineers, developer, planners, and everyone working together*" (I12). An expert with more than 30 years of experience in green infrastructure design on buildings mentioned that the team needs to be "*appropriately qualified and people with experience in that particular area, such as green roofs and green walls*" (I01). Also, one participant I07 emphasised that "*you cannot just have people espouse the knowledge without experience*". Input from the design team might "*request that the architects modify their design*" (I10) to mitigate various risks such as fire risk. Otherwise, trees might be excluded in the detailing or construction stages or generate elevated risk or failure after their implementation. Table 2 summarises whom the participants indicated were the necessary experts to be included in the design of trees on buildings.

4.1.3. Rationale and building style

Identifying the implementation rationale of trees on buildings based on the building style is essential to a successful implementation. This will enhance the design, success, and developers' acceptance (I04 and S58). Regarding the rationale for implementation, I14 argued that "*many technologies and materials can enhance [a] building's sustainability, reduce [it's] energy consumption, or absorb carbon. They are cheaper and might be more efficient than sky gardens, while other benefits, such as space usage and lifestyle, are unarguable, and they are our selling point for [the] sky gardens*

Table 1
Coding themes of the results of the survey and semi-structured interviews using NVivo showing the number of participants and references for each theme.

Theme	Number of participants	Number of references
Selection rationale		
Enhance the environment	61	119
Enhance building aesthetics	37	66
Enhance air quality	32	36
Enhance building users' health	20	37
Increase building energy efficiency	17	31
Enhance users' lifestyle	17	32
Marketing strategy	14	30
Enhance the thermal comfort	13	22
Increase roof usage	12	21
Increase building financial value	10	18
Climate change mitigation	10	17
Increase the biodiversity	8	12
Increase the shade on the roof	8	13
Stormwater delay and water harvesting	6	9
Increase building sustainability	4	4
Decision influencing factors		
Maintenance requirements	54	131
Trees selection and planting	30	64
Cost	23	41
Design team	21	50
Climate considerations	13	31
Location and Cross shading	10	18
Survival and establishment	7	16
Building theme	3	6
Implementation requirements		
Planter design	44	93
Irrigation	24	59
Soil media	18	37
Tree anchoring	15	23
Drainage layer	13	26
Planting techniques	7	10
Implementation risk		
Wind and storms	27	56
Water proofing	25	47
Roots	24	45
Weight and building structure	24	44
Dropping parts	16	25
Fire risk	10	29
Plant disease	8	18
Tree characteristics		
Growth rate	9	17
Size	9	13
Climate adaptation	7	11
Tree form	4	6
Wind and storms resilience	4	7
Trees stock	3	7
Longevity	2	4

idea". A few participants agreed on the importance of identifying the building theme from the outset to streamline the design process and align the selection of appropriate trees. For instance, I04 pointed out that "*the planting species really come down to the theme of the building, whether there is going to be native plant species, or there is going to be some sort of [non-native] tropical [theme]*", which will be reflected in the planter designs and their requirements. It will also facilitate the understanding of which tree size needs to be chosen. Similarly, if the trees are not for shade, the design options and the ease of design can be increased. "*We can have two or three small trees [rather] than having a high and big tree [which are] harder to plant [on the building]*" (I11).

4.1.4. Guidelines and precedents

Overall, participant responses indicate a lack of guidelines and design precedents for trees on buildings and the available technologies for their implementation. For instance, "*irrigation [technology] over the last ten years [has not been changed], and the planter structure and how a planter works has not been approached*" (I04). I06 added, "*there is a lack of industry knowledge, and industry expertise needs to be lifted*". However, this should not be a burden as "*there is not always rules around what you are trying to do when you are innovating*" (I02), and "*experts in this field should collect any helpful guidelines from their city councils, trust their [own] knowledge and expertise, and be innovative*" (I14). A few participants (18%) mentioned that consideration of the local climate is critical regarding precedents. For instance, I05 discussed that "*Southeast Asia and Singapore, that is where they are all looking at as an example, but it does not necessarily mean that [those precedents] are going to work well in a place like Sydney or Melbourne as they've got different climatic conditions*". In addition, (I14) argued that "*case studies of sky gardens could be taken as an exemplar for the techniques, but not as replicas, because the climate might be different*", and S6 provided the following example "*There are some interesting techniques which consist in building large columns that can support both the building and a giant tree pot on the top. [For example], in China, the 1000 trees housing project of Heatherwick*". I05 and I07 emphasised the importance of conducting research and critically analysing the results before applying them, otherwise "*we will end up with a lot of bad examples, and then the bad examples will set a precedent for a lot of clients*" (*I05)*.

Table 2
List of identified experts required to design trees on buildings and their role in the design process, presented by order of frequency from the expert survey.

Expert	Role	Order of frequency cited
Architect	Main building designer	1
Landscape Architect	Main landscape designer	2
Irrigation designer	Designs the irrigation	3
Wind and microclimate expert	Assesses wind loads and the predicted microclimate	4
Urban planner	Provides an overview of the building based on the urban context, not in isolation	5
Structural engineer	Studies the structural loads	6
Soil scientist	Provides advice on the appropriate soil mixtures	7
Access expert	Studies safe access for installation and maintenance	8
Fire engineer	Designs fire mitigation systems and mitigate fire risk	9
Hydraulics engineer	Designs water requirements and deals with excess water	10
Local urban farmer	Provides advice on the local and appropriate plants	11
Horticulturalists	Assists in trees and low canopy plant selection and soil requirements	12

4.2. Identified analysis and studies required for trees on buildings

4.2.1. Outdoor features analysis

Microclimate analysis covering the location of trees on buildings and the surrounding design environment seems essential to address the design requirements of the trees. Almost one-fourth of the participants (22%) highlighted the importance of undertaking a microclimate analysis to inform the design of the trees on the building, I12 even specifying "*more important than anything else, doing a microclimate analysis, […] because even one building would have completely different environments, each face, and that will stipulate what trees you would specify*", and "*all environmental considerations need to be taken into account - especially wind and light*" (S51). Some participants (32%) mentioned that a wind study is essential considering speed, exposure, turbulence, tunnels, and uplift to identify the suitability of the tree planting locations, suitable trees species and forms, and requirement for rootball anchoring and tree stability. Natural light (sun exposure) and shade analyses are also essential "*to select tree species that are going to produce healthy compact specimens for the light conditions*" (I13). There needs to be suitable light conditions; otherwise, "*you end up with trees chasing light, so maybe things growing at a 45-degree angle*" (I07).

4.2.2. Pre-design studies

Tree selection and planting strategies need to be carefully studied before starting the design process of green roof settings. Most participants (72%) described the tree selection process as the most challenging, "*the species selection, where you put them, how to keep them alive, and how carefully you select them to exist, and where on a building is definitely risky all around*" (I02). As already highlighted previously, tree selection should align with the building theme, as there are many purposes for trees on buildings, such as aesthetics, shading, windbreaks, and biodiversity etc. Although each broad climatic zone will influence tree selection, the microclimate could differ even in the same climate or building, so even more detailed climatic studies should be undertaken.

Some participants (29%) emphasised that the selected trees should be local/indigenous species or able to live in a similar local climate, able to adapt to challenging conditions, have low growth rate, high longevity, non-aggressive roots, require limited maintenance, and be able to tolerate drought and disease. Trees should also be planted in an appropriate location, considering their form, seasonal changes, and future growth. Beyond tree selection, the implementation of trees needs careful planning. A few participants (8%) identified that selected trees are frequently changed to that which is available at the time of implementation, which changes the project style, with I01 specifying, "*I generally find that if we want to get the best selections, we need to get the specific species of trees grown for the project*". Additionally, 8% of the participants mentioned that selecting other plants such as shrubs and ground covers should be planned carefully considering their mature sizes and avoid the proximity of plants inside the planter to ensure the success of all plants as "*planting density is a real issue*" (I03) since plants will compete for water and nutrients, which might result in some plants failing.

Soil media volume and quality studies are needed to ensure successful establishment and flourishing of the selected tree species and their success. Tree species are not identical and require different soil volumes "*there is no rule of thumb regarding soil volume. Each tree has its own needs. For example, a* 7 m *Phoenix dactylifera needs at least 1.*2 m *[depth], while most medium canopy trees do not need more than 0.*6 m *[depth]*" (I14). I13 added, "*root systems spread laterally, so you do not need a huge depth*". However, participants were split into three groups regarding perspectives on soil volume. Some participants (19%) called for deep substrate up to 1.8 m, while 13% argued that trees do not need more than 0.6 m, and the last group (68%) were not sure about the required depth. Therefore, consulting more widely with urban farmers and nursery experts is likely to be essential. Designers should "*make sure they have enough media for trees to grow happily, healthily and [in a] structurally sound way*" (I13), and not provide more than enough soil to avoid the increased dead loads and slumping as "*soil slumping is a big issue*" (I03). Regarding soil media quality, I01 stated that "*a lot of what is sold at landscape yards as soils is really only partially composted vegetable waste which contractors are paid to get rid of, and then because that is quite acid, they add some waste, which contains toxic levels of phosphates and other minerals, often heavy metals and grease, and then adjust the* pH *but to slightly alkaline, often up to 10 or 11*". A soil producer reveals "*we have done a lot of research for our soil mixes, and we designed for performance criteria rather than just complying with standards*[…] *media design is all about creating enough porosity and soil for root development to occur without heat, yet low organic content so that you are not going to have slippage*" (I07). Thus, as a few participants mentioned, designers and developers need to focus as a priority on the soil media performance rather than the cost to ensure they have a high-quality product that will give trees on buildings the best chance of success.

About half of the participants (51%) identify structural load considerations as challenging. Trees on buildings add heavy loads to buildings due to the planter structure, soil media, and tree species weight, which need to be studied and considered during the design stage. The anticipated loads should consider the soil media with the "*full weight [of the planter] full of water*" (I05), "*to carry the loads of grown trees*" (S20), and if the trees have fruits, the load of these also needs to be considered as "*these fruits might reach up to one ton*" (I08). These considerations can impact the success or failure of trees on buildings. For example, "*during construction in one project, we removed the tree as the structural engineer failed to assess the [tree] loads*" (S59). Designers can work towards reducing trees on buildings loads through the design process; the participants suggested that it was crucial to select the correct location that can be structurally supported (I10 and S61); select lightweight soil media (I01 and I11); select lightweight trees in critical structure locations (I03); and adjust the soil depth to suit different species requirements (I13, I06, and I12). The latter point can be either through adjustment of the planter depth designs, creating mountings over the planter for higher root requirements (I06 and I12), or adding waffle plugs inside the planter to reduce the soil volume where the total depth is not needed for particular plant species (I10, and I05).

It is also important to note that some elements of the green roof settings contain combustible materials that need to be assessed to reduce fire risk. Fire risk in green roof settings incorporating trees was reported to vary from low to high, depending on the climate, design elements, location of trees on buildings, building design, and maintenance quality. For instance, wet climates have a lower fire risk, while the fire risk increases in drier climates (I01 and S34). The planter materials and tree selection should be carefully considered to reduce fire risk. A fire engineer highlighted that "*plastic and foam materials in planters are problematic*", and plant experts need to "*provide a lot of evidence around the performance of plants, how they retain water, how they performed in different seasons, hold water in adverse conditions, apply moisture content, leaf fall conditions, contents of oils or volatile oils, amounts of resins*" (I10). After assessing the fire risk, some passive and active measures could be applied to mitigate fire. For passive strategies, a few participants mentioned building design, location of planters, and the continuity of plantings. For example, overlapped floors need to be designed in such a way as to limit fire spread. For active measures, 10% of the participants suggested that firefighting devices, including their appropriate maintenance and alternative fire escape routes in case of fire, should be considered, particularly if the trees are planted near the building edges, and there is a chance of falling parts.

4.3. Required techniques and design elements

4.3.1. Risk mitigation

There are three prevention techniques needed to support trees to withstand wind loads, protect the planter structure from the plant roots, and protect the building structure from water leaking.

An anchorage system may be used to support the trees and enforce their ability to resist wind loads. The survey revealed three favoured approaches to tree anchorage: permanent anchoring of the rootball and trunk for up to three years (18% of the participants), anchoring the trunk externally and for a short period (maximum three months) for 7%, while no anchorage was advocated by 8% of the participants. However, it can be understood from the participants that there is no evidence to support the need for a tree anchorage system, but regardless of this, anchorage systems are commonly used as a precaution to secure the trees from wind loads, particularly uplifting forces when the trees are planted near the building edges. An anchorage system manufacturer said, "*it comes back to fit for purpose. If you are going to plant a tree greater than* 3 m in situ*, you need to anchor it*", and he added, "*maybe [it is] not [needed], but we have a philosophy that we will anchor anything in a 75-litre rootball and above because we want to guarantee performance and it is a very expensive exercise to fix the problem later on*" (I07). However, one participant reflected, "*I wonder if this idea that we need anchors is actually because people do not understand tree root systems and the selection of appropriate trees for those situations and how trees are built because when I talk to many Singaporean experts, they just tell me it is not needed […] when you plant a [group of] plants, not a tree sitting on its own, the tree's roots overlap with [each other], and you basically create a solid*" (I01).

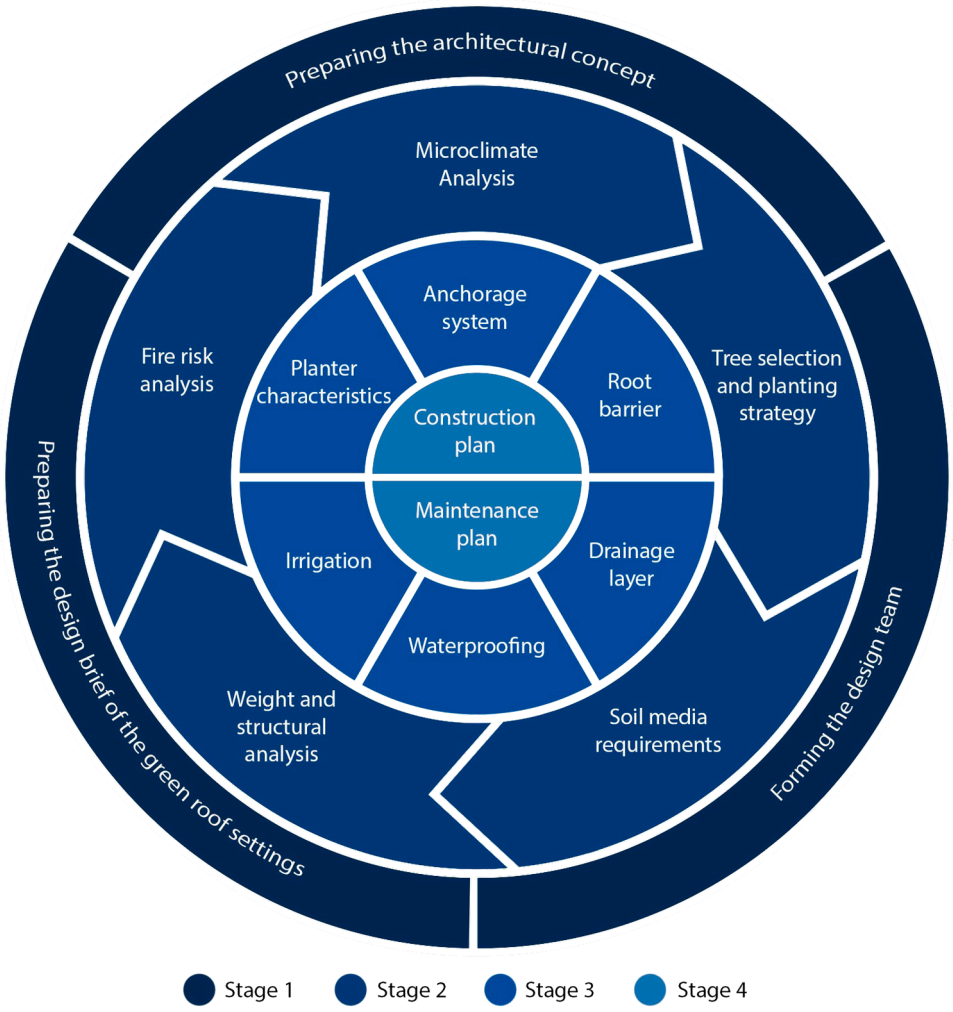

Fig. 3. A proposed design framework for green roof settings in general and trees on buildings in particular. The framework consists of four categories that are required to be followed in order from outside to inside. The four categories represent preparations, required analysis and studies, required techniques and design elements, and construction and maintenance plans.

A root barrier layer to protect the planter structure from plants roots is indispensable. Plants develop their root systems to anchor and search for water and nutrients, whether on or off the building. However, "*wind velocities high on the building can be considerably higher than the ground, and this places a lot of torque and tension on the trees, especially if they have a broad canopy with a lot of leaf surface area that is available to catch the wind*" (I06). While root anchorage is encouraged, a root barrier is needed to protect the planter and building structures from plant roots. Over one-third of the participants (35%) agreed with the negative effect of plant roots, particularly trees with aggressive root systems, such as fig trees (I03, I13, and I10). "*They can have strong roots, which may offer a bigger problem for penetrating waterproofing layers*" (I06). Overall, 42% of the participants emphasised the importance of including the root barrier layer and ensuring that the root barrier suits the selected plant species to mitigate the risk of damage to the planter and building structures.

Waterproofing is essential to protect the planter and building structure from water damage and improve the water balance inside the planter for better plant health. Half of the participants (49%) agreed on the critical nature of waterproofing, (I14) even specifying, *"when the waterproofing fails, the sky garden fails*", and I01 added that "*the most important thing is to have high-quality waterproofing […] however, it often gets damaged during construction*[…] and *instead of the waterproofing getting blamed, what gets blamed is the planting*". The failure of the waterproofing could mean failure of green roof settings "*due to water leakage the rooftop garden has been removed*" (S58) or lead to massive maintenance "*all of that media will have to come out*" (I05). Therefore, designers need to carefully select waterproofing materials to ensure the integrity of the membrane during installation and the interaction with other systems, such as the irrigation and lighting infrastructure. Also, during the design process, they need to consider appropriate water leak detection methods, and contingency plans for maintenance if the waterproofing fails.

4.3.2. *Water sourcing and balancing*

Plants need an adequate water source to ensure their success. The importance of integrating a well-designed and installed automated irrigation system was emphasised by 39% of the participants. In comparison, 11% emphasised that the irrigation system needs to be appropriately incorporated into the building infrastructure and cannot be installed at a later stage of construction. S47 reported that "*many projects have suffered from irrigation systems not installed properly due to the infrastructure provided by other trades prior to irrigation being involved in the project*". Some participants argued that advanced technologies to facilitate water distribution and monitoring are needed (I04, S58, I10), such as using a combination of subsurface drip irrigation, deep root watering devices, flood bubblers, flow sensors and soil moisture monitoring systems (S47, I03), "*the more you invest in the irrigation system, the better results you will harvest*" (I14). The irrigation system must be designed to

address the different needs of planted species, match with the soil media design, and consider seasonal variations: "*it has to be implemented correctly has to be designed correctly for water-saving conservation measures, not only for keeping plants alive*" (I04), and "*it should enable flexibility in delivery, and by that, I mean, irrigate by aspect, not by level*"(I07). The irrigation system is also considered an active method for mitigating fire risk (I04, I05, I10), as it keeps the plants "*moist and green, meaning [the buildings] are more resistant to fire*" (I10).

A well-designed drainage layer is essential for proper plant growth and the ability of the planter to control water-related issues, particularly the balance between water surplus and deficit. Some participants (20%) agreed on the importance of a drainage layer to the proper functioning of the planters, yet S48 and I01 revealed that they have experienced a few plants failing due to poor drainage of the planters. Many types of drainage layers can be used in the planters to suit the planter situation and the surrounding conditions. In some cases, with limited rainfall and irrigation, there is *"no need for a [physical] drainage layer, but an excess water outlet at the end of [a] slope in the bottom of the planter is needed*" (I14). It can be concluded that selecting the most appropriate drainage layer for the planter is an essential task to provide the correct water balance and to support plant health.

4.4. Construction and maintenance

4.4.1. Construction plan

About half of the participants (51%) agreed that expertise is required for trees on buildings construction and needs to follow a detailed construction plan, "*you need specialists in landscape construction design and construction companies, because, without that, you end up with a disproportionate outcome, you get an outcome based on hopes and desires rather than the backpressure of performance*" (I07). The construction plan should include detailed costing for all the green roof settings elements, "*quite often there is a budget issue that is causing irrigation to be cut back on and drainage to be cut back. That is because other trades throughout the project have gone over budget*" (I04) argued, and the absence of these systems might cause the failure of the green roof settings. In addition, project management is of utter importance, "*some of the biggest challenges is access to cranes, so it is a logistical exercise through construction, to make sure and a lot of the time the builder who builds the building has the crane […] unfortunately, we have had a couple of projects where we have missed the trees just through poor coordination*" (I05).

4.4.2. Maintenance plan

Long term and ongoing maintenance are recognised as the key to success after construction by 89% of the participants: "*if things are not watered and maintained properly, then all those benefits actually become very harsh and negative*" (I08). In an iconic project, due to poor maintenance "*over 50% of the green walls died, and 40% of the planter boxes died or needing serious work to rehabilitate*" (I07). Therefore, in addition to the ongoing maintenance, "*at least fortnightly monitoring by a specialist is needed*" (I04) to keep the trees and other plants well maintained, because "*if you are having irrigation issues, or pests and disease, then that is going to be a problem*" (I03). The maintenance plan must be communicated to residents and the body corporate as any *"unplanned planting [may complicate the] maintenance, especially when [there is an] irrigation system in the planter*" (S58). Also, a few participants mentioned that the body corporate should be aware of ongoing costs associated with green infrastructure maintenance and its importance to ensure they succeed. The majority of the participants (73%) emphasised that the maintenance team must include a variety of experts who understand the different garden maintenance aspects, "*you need to have a bit of everything, so your team needs to have [a] Horticulturalist, needs to have plant safety, needs to have building experience, needs to understand the body corporate*". In addition, I13 added, "*it is not just about species, it is a species into that nursery practices that are probably pruning [and well maintained]*". The most common experts and considerations mentioned as part of a successful maintenance program were an arborist, botanist, access, fertilisation, disease, and irrigation.

4.5. Summary and a proposed design framework

To integrate the required preparation, design, implementation and maintenance requirements, a generalised framework for the design of green roof settings, and trees on buildings in particular, was developed based on the emergent needs identified by industry experts (Fig. 3). The framework consists of four sequential stages of design, namely:

- Preparation.
- Required analyses and studies.
- Required techniques and design elements.
- Construction and maintenance plans.

In the first stage and after preparing the architectural design, the architect and landscape architect need to prepare the design brief and select the design team. In the second stage, the selected team needs to prepare the required studies and draft the initial design of the green roof identifying the tree species and locations. Once the studies are complete, the design needs to be reassessed in light of the results. Some of the studies might need to be conducted both before and after the design is drafted to confirm the design's suitability. Such studies could include an analysis of the microclimate, fire risk, the weight of planters, and structural loads. The next stage is to prepare the construction documents, including the technical details explicitly for the green roof elements and specifically for trees and their planters, which should be guided by the studies above. The last step includes preparing the required construction and maintenance plans to ensure the ultimate success of the green roof settings and trees on buildings in particular.

5. Discussion

This paper investigated the barriers encountered in the design of trees on buildings with a survey and semi-structured interviews to uncover the current state of industry knowledge and best practices regarding the design process of trees on buildings. These best practices have been combined and summarised to generate a systematic design framework as the main output of this study. In addition, the study also provided expert opinions regarding the literature, policies, and design challenges of trees on buildings. The experts clarified that most of the available information currently relates to green roof settings without trees and emphasised the paucity of knowledge regarding trees on buildings. This is maybe the highest level of design barrier that was evidenced. Although there is a high similarity between green roof settings without trees and the ones with trees, the latter has more complex requirements due to the existence of trees. Additionally, four other challenges were identified throughout the design process of trees on buildings, and are discussed in the following paragraphs.

Usually, the first design stage includes essential preparations containing the architectural design concept, the brief of green roof settings (e.g., background, rationale, style, guidelines, precedent, program), and the design team selection. Some of these preparations might be developed during the design process, while it is essential that others, such as the selection of the design team, are addressed before starting the design. As mentioned by the participants, the absence of a well-selected multidisciplinary design team increases the challenges during the design, construction, and management of trees on buildings. In addition, it might lead to failure, cancelling the construction, or acquiring the development approval of buildings incorporating trees. Consequently, stakeholders should evaluate the design complexity of trees on buildings at every decision-making level and be aware of the different requirements and support needed while establishing the design team. Incentives could be developed for the construction industry to include a well-qualified design team at the start of the design process. However,

as the industry is new, flexibility must be maintained as knowledge and experience are the essential factors for the success of trees on buildings and the specialists needed to support that success. For example, in this study, ecologists were not listed as required experts in the design process of trees on buildings, but as urban biodiversity becomes increasingly emphasised, biodiversity-sensitive design experts may need to be included in future [39].

Other challenges identified in the initial stage concern the pre-design studies, which provide essential knowledge about microclimate, tree selection and planting strategy, soil media volume and quality, design element weight and structural capacity, and fire risks. Although these investigations are important for the success of the project, this study shows that some of these aspects are ignored or not performed adequately. Therefore, it seems of the utmost importance that policy-makers address these issues. For instance, building approvals could be changed to include these studies as an essential part of the required design documentation. This would not only contribute to enhancing the expertise of those involved in designing trees on buildings, but it would also become a quality guarantee for owners and users of the building.

The third category of identified challenges regards techniques and design elements, such as the tree anchorage system, root barrier, waterproofing, irrigation, and drainage. These design elements are needed, and this study shows that they are typically easily incorporated as they are similar to the requirements for typical green roofs. There is a larger body of developed knowledge for these design elements, except regarding tree anchorage systems. However, even for green roofs, there is no specific legislation or standards that focus on the elements and components needed for successful design. The low quality of materials used for the above-mentioned design elements might result in a failure in the short term, leading to trees on buildings failure. For this reason, incentives should be developed regarding minimum standards for these elements.

Finally, this study has revealed that challenges also exist regarding construction and maintenance plans. They are needed to facilitate the installation process and increase implementation success. These plans are typically not considered during the design process, and there is no supporting legislation to address these requirements. Consequently, incentives should be developed to include construction and maintenance plans as required documents for building approvals. This would align with an overall building life-cycle approach and contribute to enhancing the overall quality of the project.

To mitigate the aforementioned challenges and increase the chances of successful implementation, the authors recommend using the framework outlined in this study to systematise the design and implementation processes of trees on buildings. This design framework integrates and synthesises worldwide best practice regarding trees on buildings, up to the date of this study, and recommends the main assessments that are needed to mitigate anticipated risks. It is expected that this research framework will enhance the understanding of the implementation process and requirements of trees on buildings, yielding an increase in their implementation and success.

5.1. Policy implications

One of the main findings of this study is that policies related to trees on buildings need major revision to facilitate implementation of best practice and avoid unnecessary mandated requirements and contradictions. Trees on buildings represent an innovative technology with the potential to mitigate climate change and provide many other environmental benefits. Therefore, policies and building codes should facilitate their implementation and encourage developers to include trees on their buildings. However, some existing policies hinder their implementation or unnecessarily increase the design requirements (e.g., soil depth, required studies, and limitations on plant selection) such that developers and designers avoid or are discouraged from implementing trees on their buildings. For instance, Brisbane City Council (Australia) requires at least 1.2 m media depth for trees over 5 m [40]. This requirement might be ideal for some tree species but is excessive for some shallow-rooted species or columnar trees. These compulsory requirements increase the cost and structural complexity of buildings, which can in turn unnecessarily discourage implementation. As a result, the requirements for trees on buildings (soil depth, for instance) should be flexible and supported by evidence, and constantly revised as more information becomes available to keep cost and implementation complexity to a minimum while ensuring best practice is followed. Keeping a balance between what is mandated and what remains risky and evidence-based would motivate this new industry to innovate and incorporate new knowledge as it becomes available.

Furthermore, many housing authorities and city councils require a specific distance to be kept between trees and buildings, for instance [41], which is confusing for developers wishing to integrate trees within their built structure and hinders the building approvals process. It is, therefore, imperative that policies related to tree distance from buildings are amended to facilitate the implementation of trees on buildings. Similarly, most city councils provide a plant selection guide for the built environment [42], yet lists of plants deemed suitable for trees on buildings is often limited and constrained to a few species which substantially limits future design possibilities and potentials. Tree species guidelines, therefore, need to be updated to expand opportunities for trees on buildings, including the range of suitable species, with mechanisms for further expansion available as industry experience grows. It is crucial that motivation and encouragement is embedded to increase the tree species selection for implementation on buildings. Developers also need to have the opportunity to trial new species, potentially through a risk-based framework supported by preliminary studies of plant traits and analogous situations in nature.

Lastly, some city councils have included a requirement for studies to be conducted as part of the approval process for buildings that incorporate trees, such as fire risk studies[41]. The review of these studies is typically conducted by authorities outside the city council with specialists unfamiliar with the design of trees on buildings, which complicates and delays the building approval. As much as the above-mentioned studies are highly encouraged, these studies need to be conducted by experts in trees on buildings to help facilitate the approvals process.

5.2. Research implications and future studies

Due to the limited literature concerning trees on buildings, it is expected that over time further research will be needed to improve the proposed design framework in this study. As of this date, there is limited literature considering tree selection for trees on buildings, namely Law, Hui [5], Abuseif, Dupre [14], Namba, Inoue [43]. Similarly, no studies consider the required soil volume for different trees nor the effect of limited soil volume on the growth and lifespan of the tree except for one study conducted by Rahman, Fleckenstein [44], which tested two containerised tree species at ground level. These required studies and the effect of the planter setting are critical for tree selection. Participants also highlighted different approaches to using anchoring systems to support trees to withstand wind loads, but the literature in this area is scarce. Whereas a few studies assessed wind loads on some tree species on buildings [45–47], and other studies considered root anchoring at ground level [21,48], no literature specifically addresses tree anchorage requirements for trees on buildings. Therefore, researchers are encouraged to focus research efforts on studies to cover the above gaps in knowledge to facilitate the implementation of trees on buildings.

Lastly, the proposed framework in Section 4.5 presents a general systematic approach that can be used as a foundation for each city council to develop their own framework tailored to their specific context. This may include learning from existing standards, policies, and successful local examples. Although there might be differences due to the cities' climatic conditions and policies, essential design processes, elements, and initiatives can still be generalised. For instance, the

Development and Construction Society (FLL)-Green Roof Guidelines [35] provide rich information regarding the design requirements, implementation, and maintenance for various green roof settings, including trees. Sjöman and Nielsen [25] and Hitchmough and Dunnett [49] provided substantial guidelines and design approaches to integrate trees in both urban spaces and confined locations, which is extremely relevant to trees on buildings. The Singaporean experience in this regard presents a good example to learn from, including the handbook on developing sustainable high-rise gardens [50], as well as guidelines for trees on rooftops [29], and their funding schemes to increase the implementation [51]. The design process and implementation of successful examples also provide a great source for establishing these frameworks and enhancing the design process. These successful examples can also be integrated as precedents in these frameworks, such as the Freshwater Place Green Roof and Treehouse Apartment in Australia [34,52]; Park Royal Collection Pickering, Kampung Admiralty, and Oasia Hotel in Singapore [53–55]; and the Bosco Verticale in Italy [56].

5.3. Study limitations

This study investigated best practice design processes for trees on buildings based on several contexts (e.g., climatic conditions, geographic locations, the background of the designers and multidisciplinary experts in the field). To collect information about the design practices in different climates and contexts, a worldwide survey was undertaken. However, the exclusive use of English might have prevented non-English speakers from participating and limited the comprehension of some experts. Furthermore, the survey responses originated only from 17 countries, with a predominance of Australian responses (43%). Future research might focus on other parts of the world, notably Asia, which was underrepresented and where the practice of trees on buildings is widespread. It is also worth noting that architects and academics participated in the survey but did not elect to participate in the follow-up interviews. Although academics are not primary actors in designing and implementing trees on buildings, they may influence the education of those who are. As for architects, it would be crucial to understand their lack of interest.

Additionally, the analysed results of this study show that a few participants did not distinguish between green roof settings with and without trees and provided responses based on a general assessment of green infrastructure needs on buildings rather than trees on buildings specifically. In the same way, many academics and architects who participated in the study strongly support the implementation of trees on buildings, yet the survey showed that they do not fully understand the required design elements or the design process. This was also highlighted in some of the feedback given by landscape architects and installers. Finally, green infrastructure, the core of ecological engineering, aims to restore the ecological balance and create harmony between the natural and built environments. However, ecologists were notably absent from participating in this investigation, and their absence needs to be investigated and redressed more generally as the industry develops.

6. Conclusion

This study investigated the barriers and provided a framework to enhance the design and implementation process for trees on buildings. This research demonstrates that the inclusion of trees on buildings adds more design challenges compared to standard green roof settings with low canopy vegetation. These challenges need to be addressed throughout the design process to ensure implementation success. Therefore, the authors suggest that designers, developers, and policy-makers adopt the presented design framework to guide their design decisions to achieve the best outcomes for trees on buildings. The design framework resulting from this study consists of four categories: preparation, required analyses and studies, required techniques and design elements, and construction and maintenance plans. In addition, the paper discusses the existing policies and literature regarding trees on buildings based on feedback from experts in the field, who highlight the lack of relevant available knowledge. Three main policy recommendations emerge from this study. First, the requirements for implementing trees on buildings (e.g., soil volume and fire mitigation requirements) should be flexible if the design is supported by evidence even if it does not comply with the current policies. Second, consistent policies related to tree planting distances from buildings should be amended to consider trees on buildings and applied nationally. Finally, the tree species selection guidelines should be widened to include requirements for trees on buildings with greater participation from ecologists, urban farmers and nursery specialists. Further studies are recommended on tree species selection, optimal soil volumes and configurations for different tree species, the effect of limited media on tree vigour, and the need for anchoring systems for trees on buildings.

- The paper provides a framework for designers and decision-makers that help enhance the buildings and the built environment. Specifically, by reducing the design challenges of trees on buildings and increasing their implementation.
- The paper presents areas within the existing policies and literature that need to be improved to widen the knowledge regarding trees on buildings and reduce the challenges to their implementation.
- The paper highlights challenges and issues that must be considered by designers and decision makers not only to enhance the

Table A1
Survey questions and their type. CE= Closed-ended question, OE= Open-ended question.

Question type	question number	Question
CE	1	What is your job/discipline?
CE	2	What country are you based in?
CE	3	Have you participated in designing/constructing buildings that incorporate trees/sky gardens?
CE	4	Describe your role in the implementation of trees/sky gardens on building if you participated before or you intend to participate in the future?
OE	5	What is most essential for you when implementing or considering trees/sky gardens on buildings?
OE	6	Would you encourage your client or your company to design or construct buildings that host trees/sky gardens on them? Yes/No? And Why/Why not?
OE	7	What benefits do you think trees/sky gardens will bring to the building, its users, the environment, and your job/discipline?
OE	8	Scholarship shows that implementing greenery on buildings might increase the overall building cost. Do you agree with that? If no, why? If yes, do you think Implementing trees is worthwhile and can balance out the price and why?
OE	9	Are you aware if there are any policies around implementing trees/sky gardens on buildings? If yes, do you think they are helpful and why? If no, would it help if they were there and why?
OE	10	What areas or issues do you think still need improvement to support and widen the implementation of trees/sky gardens on buildings?
OE	11	Do you think implementing trees/sky gardens on a building is risky? If yes, why, and what are the most concerning risks for you, the building, and the building users? If no why?
OE	12	Do you have experience with current construction techniques? If yes, please list them below.
OE	13	Do you feel confident to use integrated planters with the building's structure and the available anchorage techniques for implementing trees on buildings in your projects? If yes, why? If no, why, and what do you think should improve?
OE	14	Is there any challenges or success you have faced or heard about during implementing trees on buildings? What happened?

implementation of trees on buildings, but also to reduce the cost of the implementation and the maintenance after the implementation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Appendix

Table A1.

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