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## Reference:

De Bock Anouk, Belmans Bert, Vanlanduit Steve, Blom Johan, Alvarado Alvarado Allan Augusto, Audenaert Amaryllis.- A review on the leaf area index (LAI) in vertical greening systems

Building and environment - ISSN 1873-684X - 229(2023), 109926
Full text (Publisher's DOI): https://doi.org/10.1016/J.BUILDENV.2022.109926
To cite this reference: https://hdl.handle.net/10067/1945750151162165141

# A review on the Leaf Area Index (LAI) in vertical greening systems.

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## Abstract:

The leaf area index (LAI) is a key dynamic parameter in Vertical Greening Systems (VGS). It quantifies the total amount of leaf area in the canopy and largely determines the extent of co-benefits of VGS. Whereas many studies on VGS discuss the importance of the LAI, only few elaborate on the parameter itself, how it is determined and what the current limitations are in VGS. Moreover, although there is scientific consensus on the importance of LAI in VGS, specific non-destructive monitoring techniques for continuous LAI monitoring appear to be absent, which results in limited overall data on the LAI of VGS under different spatial and temporal conditions and problems in quantifying the benefits of VGS in practice. To fill these gaps, this paper specifically focuses on the LAI of VGS and its monitoring techniques. An overview of existing LAI monitoring techniques in the field of VGS is presented. To arrive at dedicated techniques, this is complemented by a thorough analysis of LAI monitoring techniques used in other research fields, e.g. agriculture and forestry. It is established that two indirect techniques for LAI monitoring are currently available in the VGS sector, but a proper standardized sampling methodology currently lacks. Monitoring techniques used in other sectors offer opportunities for developing dedicated monitoring methods for VGS, but require further research due to the specific features of VGS systems. Furthermore, guidelines are proposed for a more standardized LAI determination of reporting of LAI values in VGS.

## Highlights:

- The importance of LAI in characterizing the benefits of VGS is highlighted
- LAI of VGS is poorly established and standardized monitoring techniques are missing
- An analysis on the shortcomings in determining and reporting the LAI of VGS is made
- A standardized sampling and reporting method is provided
- Other sectors in which LAI is better established can provide valuable insights

**Keywords:** Leaf Area Index (LAI); Vertical greening systems (VGS); Indirect LAI monitoring techniques; Living Wall Systems (LWS); Green Facades (GF); LAI-sampling method

## 1. Introduction

By 2050, around 70% of the population will live in urban environments [1]. Moreover, due to climate change and how we organize and build our cities, there is an increased risk of floods, droughts, pollution, rising urban temperatures, loss of biodiversity, vegetation, and land degradation [2–5]. Consequently, urban habitats are under pressure, and adaptations to our way of living together are needed. Within this context, bringing more greenery into cities is a universally accepted adaptation measure. Greenery combats the effects of climate change and contributes to keeping the urban environment comfortable and healthy to live and work in. However, as there is little ground space left to accommodate traditional greenery, such as parks and avenues, innovative Building-related Greenery Solutions (BGS) need to be considered. Since building envelopes generally have a larger vertical facade area than horizontal roof areas, Vertical Greening Systems (VGS) offer the largest untapped area to provide additional green space in cities. Still, compared to horizontal BGS (green roofs), VGS remain underexposed. Even so, VGS are said to deliver similar benefits to traditional greenery, viz. cooling, sound attenuation, air purification, improved mental health, increase in biodiversity, etc. [6–13].

Many of the benefits of VGS can be linked to the relative amount of leaf area in their canopy. The total leaf area is expressed in a parameter, named the Leaf Area Index (LAI) [14]. This seasonal and systemic parameter, which was first described in the domain of agriculture and forestry, describes the total leaf area of a greenery system relative to the underlying ground. The LAI is considered an important vegetation parameter for VGS because it determines to a large extent the benefits that VGS offer, such as thermal cooling [11,15,16], capturing particulate matter [13,17–19] and noise absorption [8,20]. The LAI is also an important indicator of canopy health, for example, a lowered LAI value can be an indication of drought stress or possible diseases in the canopy [21,22].

While previous studies have repeatedly highlighted the importance of the LAI as a key performance indicator in green facades [10,14,16,23,24], no study has ever specifically focused on a broad examination of the techniques used for LAI monitoring in VGS. Similarly, no study has investigated the possibility for dedicated LAI monitoring techniques for VGS and the benefits these could offer, taking into account VGS particularities. Finally, while the problems arising from the absence of a standardized LAI reporting method for VGS are clear, guidelines for standardized LAI reporting are absent. Further exploration of LAI therefore is a crucial step for the further development and wider implementation of VGS in our cities.

## 2. Objectives and article structure

Although dedicated research on LAI and LAI monitoring in the field of VGS is limited, several observations on the LAI of VGS can be found in research articles. This review paper aims to aggregate this information, critically assess it and expand it with new insights and ideas. On the one hand to highlight the importance of LAI in VGS and on the other hand to uncover the main obstacles that prevent its broader and more frequent use in the VGS sector. Besides describing the relevance of the parameter in VGS and outlining the issues regarding the parameter, this review article aims to offer relevant information for an improved determination and reporting of LAI values in VGS. The LAI monitoring techniques used in other research areas are elaborated to examine whether these techniques could be applied to VGS, either as an addition to or as a replacement for current LAI determination techniques.

This paper is structured in the following way: first, theoretical background and relevant terminology are provided regarding VGS and LAI (section 3). Next, section 4 zooms in on the relevance of the LAI in the domain of VGS. Here there is a focus on the relationship between the LAI and the benefits associated with VGS. Section 5 covers the measuring techniques used, both inside the VGS sector and in other sectors, i.e. forestry and agriculture. In section 6 we will assess the advantages and limitations of each measuring technique presented in section 5. Moreover, the shortcoming in determining and reporting the LAI values will be presented and recommendations will be given for a uniform and robust LAI determination and better reporting of the parameter. The last section provides the main findings from this review paper and possibilities for future research.

## 3. Theoretical background and terminology

While the emphasis of this paper is on the measurement techniques to determine LAI in VGS, this section explains some fundamental and basic concepts related to VGS to better understand the remainder of the paper, i.e. the different types of vertical greening systems and the general concept of LAI, both within and outside the domain of VGS.

### 3.1 Vertical greening systems (VGS)

In vertical greening systems (VGS) two large groups are distinguished: green facades and living walls. In green facades, the plants root in the soil and climb the vertical wall, with or without a climbing aid. In these systems, the plant choice is limited to climbing plants. In living walls, the plants are rooted in a vertical growing medium mounted to the wall. In this type of system, an irrigation and fertigation system is required to provide the plants with sufficient water and nutrients. This paper distinguishes three different system types that are shown in Figure 2 with their corresponding cross sections: **the Living Wall Systems** (LWS) (Figure 1a); **the Traditional Skin Facades** (TSF) (Figure 1b) in which the vegetation grows directly into the wall using adhesive roots and disks; and the **Double-Skin Green Facades** (DSGF) (Figure 1c) in which plants climb up on a climbing aid, thus creating an air gap between the wall and the canopy.

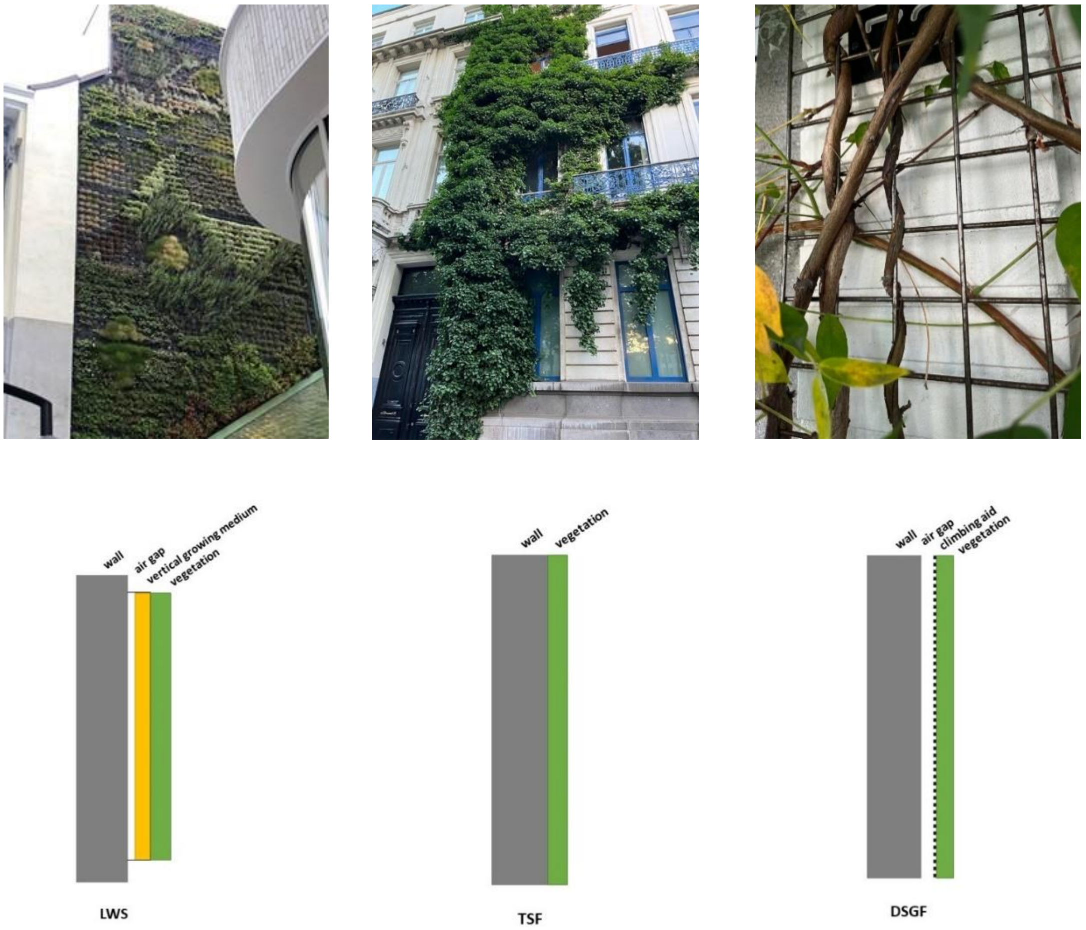

*Figure 1: Overview of different types of VGS and their cross sections: a) Living Wall Systems (LWS), b) traditional skin facade (TSF), and c) double-skin green facade (DSGF).*

### 3.2 The Leaf Area Index (LAI)

The LAI is a dimensionless and time-dependent parameter widely used across research domains to determine the amount of leaf area in an ecosystem [22,25–27]. It was defined by Watson (1974) as the ratio of one-sided leaf area in the canopy per ground unit [$m^2$ $m^{-2}$] (Figure 1) [28]. The LAI is dynamic and subject to change due to variations in internal and external factors such as plant species type, seasonality, orientation, nutrient availability, diseases, etc. [24,25,27,29,30]. LAI is considered a critical parameter in processes such as photosynthesis, respiration, evapotranspiration (ET), rainfall interception, and biogeochemical cycles in ecosystems [22,27,31].

In agriculture, the LAI is used for crop yield estimation, detection of potential diseases or damage to crops, and determining the amount of pesticides and fungicides for protecting a crop [21,32]. In these applications, continuous monitoring of the evolution in LAI values helps in forecasting crop yields and characterizing crop growth [33]. Also, in forestry, LAI is an important structural characteristic of the forest, as the forest canopy is the place where significant ecosystem processes occur [31]. In both these fields, continuous monitoring of LAI with a high spatial and temporal coverage is needed for forecasting and generating input for automated algorithms [22,34].

Whereas the LAI was initially defined for agriculture and forestry applications, LAI can also be used as an indicator of vegetation health and system performance in an urban context (e.g., in green roofs and VGS) [16,35]. The most obvious difference is that for VGS, unlike forestry and agriculture, the LAI is determined in the vertical plane instead of the horizontal plane. By analogy with the general definition of LAI, in VGS the LAI is defined as the ratio of the total one-sided leaf area per unit vertical wall area behind it (Equation 1). This again results in a dimensionless value with a unit vegetation surface area per vertical wall surface area [$m^2$ $m^{-2}$]:

$$\text{LAI}= \frac{\text{total one-sided leaf area } [\text{m}^2]}{\text{wall area } [\text{m}^2]} \tag{1}$$

Figure 2 shows the concept of LAI graphically: if all the leaves of a multilayer canopy would be harvested and projected in the vertical plane, the LAI will express how many subsequent fully covered unit layers can be formed, which in this case is three layers or an LAI value of 3.

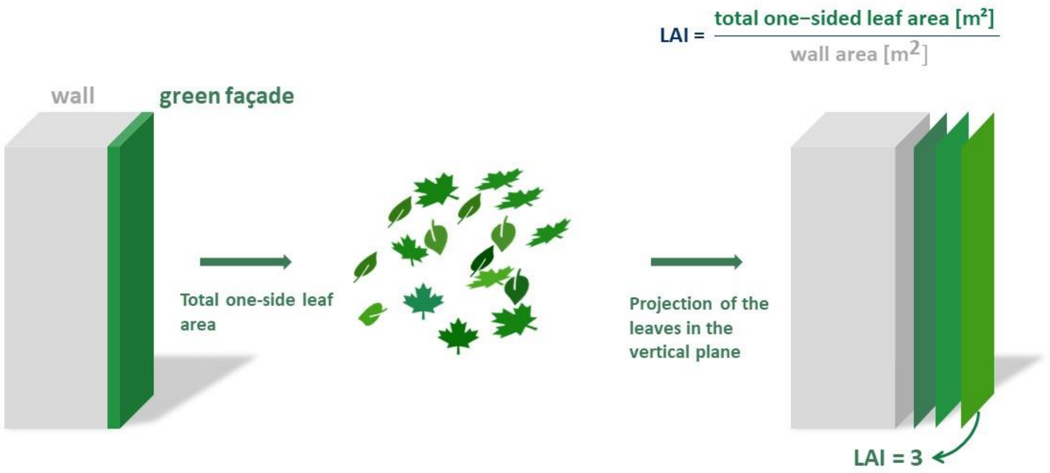

*Figure 2: Visual representation of the Leaf Area Index in Vertical Greening Systems.*

## 4. LAI and its position in the domain of VGS

In this section, relevant papers have been reviewed that show the importance of LAI in VGS. The influence of the LAI on several benefits provided by VGS is discussed, namely, thermal cooling, capturing of particulate matter, and acoustic absorption. These abilities are favored by more leaf area in the canopy. Having a good characterization of the LAI is thus important for quantifying the benefits provided by VGS.

### 4.1 Relationship between LAI and thermal cooling of VGS

Vertical greenery has multiple cooling mechanisms at the building level viz. shading, evapotranspiration, insulation (by materials and layers: plants, air gap, substrates, etc.), and vegetation creating a wind barrier [16]. Shading and evapotranspiration have the most significant effect on cooling and consequently energy savings [11,36]. The LAI is a vital parameter in these cooling processes and determines to a large extent the cooling capacity of the green facade [11,14].

Bakhshooded et al. [14] did a review on the thermal performance of green facades by analyzing the results of 26 relevant papers that reported on the thermal performance of green facades. They found a strong inverse relationship between the LAI and the temperature on the surface of the external wall behind the VGS (with a Pearson coefficient of -0.78). In other studies, a similar trend was observed. In research conducted by Wong et al. [15] the effect of vertical greenery, and the shading coefficient, on the temperature and energy consumption of the building was simulated. The outcome of this research was that there is a linear correlation ($r^2 = 0.79$) between the shading coefficient and the LAI, where a high LAI results in a low shading coefficient. The shading coefficient is the ratio of the solar radiation beneath the plant and the bare wall, meaning that a low solar radiation value beneath the plant means that the plant shades the wall effectively, resulting in a cooler wall surface. The other process responsible for cooling is evapotranspiration. Convertino et al. [11] evaluated the evapotranspirative and shading effects of green facades. They identified LAI as a key parameter that directly influences shading and the latent heat of evapotranspiration in the canopy. Viz, in Equation 2 the total radiation ($R_n$) represents the total radiation absorbed by the green layer:

$$R_n = 0.86\,(1 - e^{-0.7\mathrm{LAI}})\,R_g \tag{2}$$

| | | |
|---|---|---|
| $R_n$ | Total radiation | Radiation absorbed by the green layer |
| $R_g$ | Global radiation | Sum of solar and longwave infrared (LWIR) |

This total radiation ($R_n$) can subsequently be used to evaluate the latent heat due to evapotranspiration in the canopy by feeding it into the Penman-Monteith equation [11]. Consequently, the latent heat due to evapotranspiration in the canopy is directly related to the LAI. In more recent research by Convertino et al. [23], the effect of changing LAI values of an evergreen south-oriented DSGF in a Mediterranean climate on the cooling effect inside the building was studied. In this research, the LAI values were simulated, and one LAI value was determined directly using a destructive leaf harvesting method (LAI = 4.1). Results showed that solar transmission through the canopy decreased by 54% for every LAI unit increase. Moreover, if the LAI increased, the solar shading and latent heat increased as well. This correlation persists up to an LAI of 6, respectively (Figure 3a, 3c). For LAI values higher than 6, a stabilization of the shading coefficient and latent heat was observed (Figure 3b, 3d).

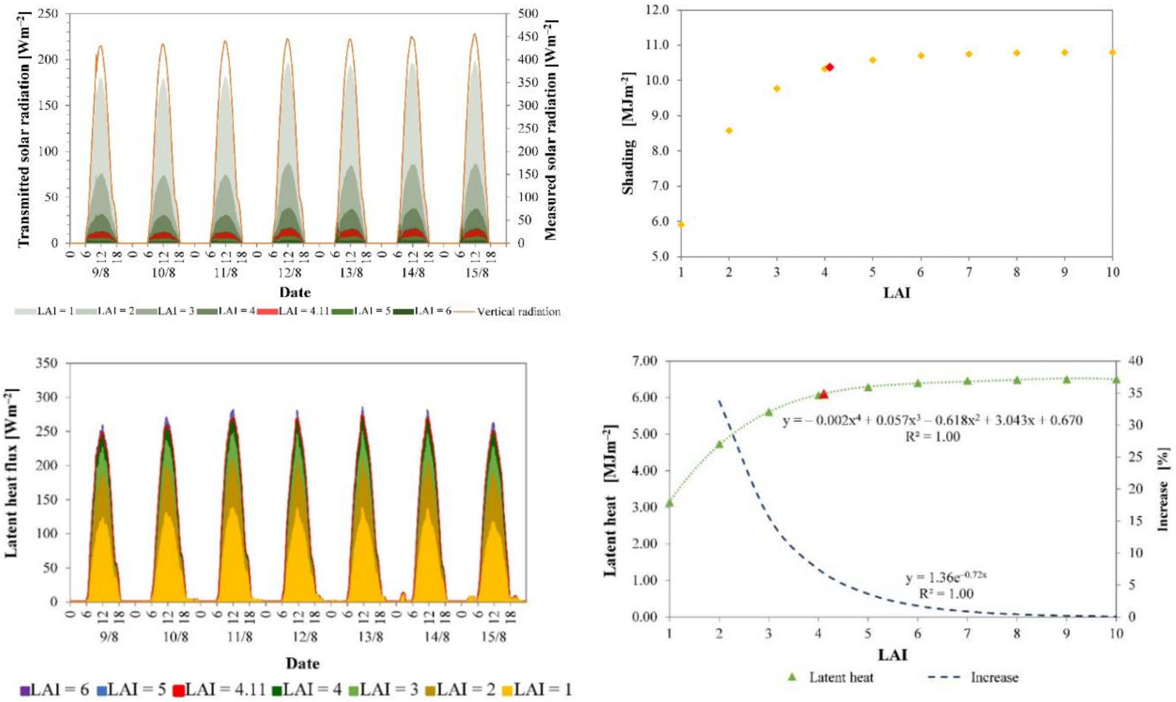

*Figure 3: a) solar radiation transmitted through the green layer simulated for the different LAI values and measured solar radiation on the vertical surface, b) daily average values for solar shading effect of the green layer for different LAI values, c) latent heat flux due to evapotranspiration of the green layer with different LAI values, d) daily average values of latent heat due to green layer evapotranspiration for different LAI values and percentage increase of latent increase of latent heat for each LAI unit increase.*

*Adapted from "Effect of Leaf Area Index on Green Façade Thermal Performance in Buildings" by F. Convertino et al., 2022, Sustainability, 14, 2966. Copyright 2022 by Anouk De Bock. Reprinted with permission.*

### 4.2 Relationship between LAI and fine dust capture of VGS

Green facades in urban areas can effectively capture fine dust and remove pollutants from the air. Several mechanisms are responsible for particulate matter (PM) mitigation, where the two main mechanisms are deposition and dispersion [13,17,18,37,38]. In the process of deposition, the particles pass a surface to which they adhere. Here, plant characteristics play an essential role. Two main categories can be distinguished, the macrostructure of the vegetation and the microstructure of the leaf surface (surface geometry, rigidity, leaf characteristics, etc.) [13]. The macrostructure is mainly determined by the LAI and the Leaf Area Density (LAD), which is defined as the total one-sided leaf area per unit volume [$m^2$ $m^{-3}$] [13,17,18]. The important factors are hence the porosity and density of the vegetation. The amount of material deposited per unit of ground area and time is calculated using Equation 3 [17]:

$$\text{Deposited amount } \left(\frac{g}{m^2}\right) = \text{LAI } v_d \text{ C t} \tag{3}$$

| | | |
|---|---|---|
| LAI | Leaf Area Index | [-] |
| $v_d$ | Deposition velocity | [m/s] |
| C | Concentration PM | [$g/m^3$] |
| t | Time | [s] |

This formula indicates that the amount of deposited material is directly correlated with the LAI, since the concentration and time are fixed parameters. The deposition velocity ($v_d$) is influenced by PM size and vegetation type (e.g., surface roughness) and is often assumed to be constant but may vary according to wind speed and the dimensions of the green wall [13]. It can be concluded that the deposited amount of PM is influenced to a large extent by LAI. Research on green facades also shows that the LAI has an important role in capturing PM. In research by Weerakkody et al. [18], the ability of seventeen LWS species to capture PM was tested. Per species, 20 leaves were microscopely tested by using an Environmental Scanning Electron Microscope (ESEM) and the image analysis software ImageJ [39]. The factors influencing the deposited amount were attributed to the LAI, leaf size, and shape. Favorable species were species with small and complex-shaped leaves with a high LAI.

### 4.3 Relationship between LAI and acoustic properties of VGS

Several components of VGS influence noise absorption depending on the VGS type. In the case of LWS, one of the most defining factors for sound absorption is the substrate layer, where the thickness and porosity are the main influencing factors [8,40]. Secondly, the vegetation layer also affects the absorption coefficient, though smaller than the effect of the substrate. In the plant layer contribution, the plant species, plant height, leaf thickness, leaf size, and percentage of growth (e.g., the LAI) play a role [8]. Wong et al. [20] were the first to assess the impact of VGS on noise reduction. This research compared the impact of different types of materials and different coverage percentages of greenery on the sound absorption coefficient, which is dependent on sound frequency. From this study, it was observed that higher greenery coverage percentages resulted in a higher absorption coefficient. As the frequency increases, the differences between sound absorption coefficients increase. At low frequencies, the differences in sound absorption coefficients among different coverage percentages are minor, whereas at higher frequencies the differences widen. A similar observation was found by the Belgian Building Research Institute [41] which studied the influence of the amount of leaf area per m² on sound absorption in mid-frequencies. This study showed that a higher leaf area per m², i.e., higher LAI values, results in a higher sound absorption from 500 Hz onwards. Pérez et al. [8,42] recommended increasing the thickness of the vegetation layer or using plant species with a higher foliage density to increase sound absorption.

## 5. Overview of techniques used for determining LAI values

In this section, various techniques for determining LAI values are presented. First, we will look at the techniques used in the domain of VGS. Next, we will look broader, at the techniques used in other research domains, such as agriculture and forestry, which are more mature since the LAI has been used much longer here and existing techniques are adapted to these domains.

### 5.1 Principles of LAI measurement techniques used in the domain of VGS

#### 5.1.1 Overview of LAI measuring techniques used in VGS

Generally, the studies that specifically report on the LAI values of VGS are limited. In total 13 papers were found where the LAI of the green facade was determined in situ, using direct methods, indirect methods, or a combination of both; these papers are listed in Table 1. Several studies use simulated LAI values or LAI values adopted from other studies [23,43–46]. Papers that only report simulated LAI values or LAI values adopted from other studies are not included in the table and are not further discussed since the focus of this paper is specifically on how LAI values are being measured in VGS.

Table 1 combines the VGS type, climate type (Köppen classification), facade orientation, canopy specifications (mixed/homogenous, deciduous/evergreen), plant species type, technique (+ used device), and the range of measured LAI values. These variables are considered the most relevant boundary conditions affecting the LAI. However, other factors may influence the LAI, such as soil type or water availability, these boundary conditions can be easily determined or described by the researcher. Pérez et al. [16] constructed a similar table, however, this table did not provide information on the VGS type, climate type, and facade orientation. Also, fewer papers are included in this research.

*Table 1 gives an overview of the used techniques for determining LAI values of studies in the domain of VGS. This table contains data on the authors, VGS type, climate type – Köppen classification, facade orientation, canopy specifications (mixed or homogeneous canopy), plant species, the used technique for LAI determination, and the range of measured LAI values.*

| **Authors** | **VGS type** | **Climate type - Köppen classification** | **Facade orientation** | **Canopy specifications** | **Plant species** | **Technique** | **Range of measured LAI values** |
|---|---|---|---|---|---|---|---|
| Wong et al. (2009) [15] | DSGF | na | na | Homogeneous canopy | *Nephrolepis exaltata* | Radiative transfer theory technique (LAI-2000 plant canopy analyzer) | 0 – 2.5 |
| Šuklje et al. (2016) [47] | DSGF | Marine West Coast climate (Cfb) | South | Homogeneous canopy – annual plant | *Phaseolus vulgaris L.* | Radiative transfer theory technique (LAI-2200C plant canopy analyzer) | 6.1 (±0.5) (one-layered)<br>7.2 (±0.6) (two-layered) |
| Weerakkody et al. (2017) [18] | LWS | Marine West Coast climate (Cfb) | na | LAI determined for 17 different plant species seperately | cf. enumeration in paper | Destructive leaf harvesting method | 0.59 – 2.85 (depending on species type) |
| Pérez et al. (2017) [35] | DSGF | Mediterranean continental climate (*Csa)* | East, South, and West | Homogeneous canopy – Deciduous | Boston ivy (*Parthenocissus tricuspidate)* | Radiative transfer theory technique (PAR Sunfleck Ceptometer) | 3.3 – 3.5 (East)<br>2.9 – 3.1 (South)<br>1.1 – 3.1 (West) |
| Pérez et al. (2017) [35] | DSGF | Mediterranean continental climate (*Csa)* | East | Homogeneous canopy – Deciduous | Boston ivy (*Parthenocissus tricuspidate)* | Destructive leaf harvesting method | 2.1 – 3.9 (East) |
| Vox et al. (2018) [48] | DSGF | Mediterranean continental climate (*Csa)* | na | Homogeneous canopy – Evergreen | *Rhyncospermum jasminoides*<br>*Pandorea jasminoides* | Radiative transfer theory technique (AccuPAR Ceptometer) | 2 – 4<br>1.5 – 3.5 |
| Li et al. (2019) [49] | TSF | Humid subtropical climate (*Cfa)* | South | Homogeneous canopy – Deciduous | Boston ivy (*Parthenocissus tricuspidate)* | Destructive leaf harvesting method | 1.21, 3.32, 4.53 |
| Lee & Jim (2019) [50] | DSGF | Monsoon-influenced humid subtropical (*Cwa)* | Northeast | Homogeneous canopy – Deciduous | *Lonicera japonica* | Destructive leaf harvesting method | 0.24 |
| Zhang et al. (2019) [51] | DSGF | Mild temperate with hot and humid summer (Cfa) | West | Homogeneous canopy | *Pyrostegia venusta* | Radiative transfer theory technique (LAI-2200C plant canopy analyzer) | 4.51 (±0.033) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Azmiah Abd Ghafar et al. (2020) [52] | LWS | Tropical rainforest climate (Af) | na | LAI was determined for four species separately | *Philodendron burle-marxii*<br>*Pyllanthus cochinchinensis*<br>*Nephrolepis exaltata*<br>*Cordyline fructicosa* | Destructive leaf harvesting method | 5.84<br>5.48<br>6.55<br>3.61 |
| Convertino et al. (2021) [11] | DSGF | Mild temperate with hot and humid summer (Cfa) | South | Homogeneous canopy – Evergreen | *Rhyncospermum jasminoides* | Radiative transfer theory technique (device not specified) | 2.2 (at $\theta=90^\circ$)<br>2.65 (at $\theta=70^\circ$)<br>*$\Theta$ = solar zenith angle* |
| Convertino et al. (2021) [11] | DSGF | Mild temperate with hot and humid summer (Cfa) | South | Homogeneous canopy – Evergreen | *Rhyncospermum jasminoides* | Destructive leaf harvesting method | 4.11 |
| Pérez et al. (2022) [16] | DSGF | Mediterranean continental climate (*Csa)* | East, South, and West | Homogeneous canopy - Deciduous | *Parthenocissus tricuspidata* | NDVI technique | 4.4 – 4.8 (summer)<br>1.7 (autumn)<br>0.9 (winter)<br>3.6 (spring)<br>*Depends on facade orientation (cf. paper)* |
| Pérez et al. (2022) [16] | DSGF | Mediterranean continental climate (*Csa)* | East, South, and West | Homogeneous canopy – Deciduous | *Parthenocissus tricuspidata* | Radiative transfer theory technique (AccuPAR Ceptometer) | Used as validation for NDVI, measured LAI values are not reported |
| Bakhshoodeh et al. (2022) [53] | DSGF | Mediterranean continental climate (*Csa)* | North and West | Homogeneous canopy – Evergreen | *Wisteria sinensis*<br>*Hibbertia scandens* | Radiative transfer theory technique (Device not specified) | 2.7 (±0.6)<br>2.3 (±0.8) |
| Lin et al. (2022) [54] | DSGF | Mild temperate with hot and humid summer (Cfa) | na | na | na | Radiative transfer theory technique (LAI-2200C plant canopy analyzer) | 1.56 – 3.61 |

Table 1 shows that from all the studies, the radiative transfer theory technique is the most used in VGS [11,15,16,35,47,48,51,53,54]. The destructive leaf harvesting method is also frequently used [11,18,35,49,50,52], while the NDVI technique is only used once [16]. It must be noted that indirect techniques for LWS and TSF lack. In LWS and TSF, only the destructive leaf harvesting method was used to determine LAI.

The remainder of this section will elaborate on how the techniques work and how they are applied in VGS.

### 5.1.2 Destructive leaf harvesting

Destructive leaf harvesting is a direct method for determining the LAI of the canopy. The leaves of the facade are harvested and the leaf areas are then measured. The first step in this method is selecting a representative plot of the vegetated wall. While there are no specific guidelines on plot sample size, the selected plot needs to be representative of the entire facade. Convertino et al. [11] and Li et al. [49] sampled plot sizes of 20 cm x 20 cm, while Lee et al. [50] sampled a plot of 30 cm x 30 cm. All the leaves inside these plots are harvested. Next, the harvested leaves are scanned using a scanner, or a photo is taken of the leaves against a white background. Then the image is loaded into an image analysis software for example ImageJ [39]. The software distinguishes the green pixels from the white pixels and consequently, the area of the green pixels is calculated. Azhmiah et al. [52] harvested 10 random leaves in the canopy. These leaves were scanned and the mean area of the leaves was calculated using ImageJ. Next, a plot was selected and the number of leaves in the plot was counted. The ratio of the total leaf area within the plot and the ground area is then calculated to obtain the LAI values of the selected plot. The obtained LAI value of the plot is then used as the generalized LAI value of the entire facade. Figure 4 shows an overview of the workflow that is commonly used in the destructive leaf harvesting method in VGS.

Pérez et al. [35] performed both direct and indirect measurements of the LAI. They sampled for the direct method at three height levels on the East orientation of the facade. The leaves on the lower level of the facade were larger compared to the leaves at the upper level resulting in LAI values that were almost two times higher for the lower levels (LAI = 3.9) compared to the higher levels (LAI = 2.1). This is because mature leaves, at the bottom of the canopy, are generally larger compared to younger leaves. These results show the presence of spatial variability within the canopy and the importance of sampling at multiple locations within the canopy to capture this variability.

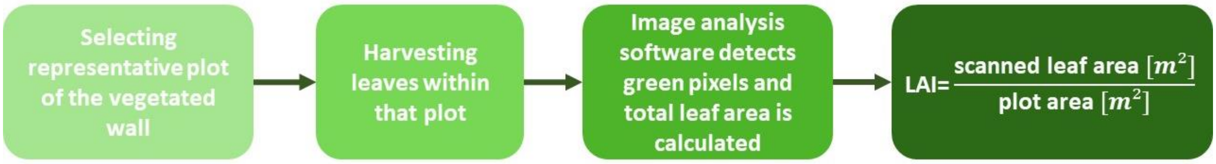

*Figure 4: Workflow for the destructive leaf harvesting method.*

Direct methods for leaf area measurements are more accurate since the area of one leaf can be measured more precisely with digital image processing compared to indirect methods (cf. section 5.1.3) [25]. However, this method is unsuitable for processing large quantities of leaves since this approach is highly time-consuming. Also, with this approach, only isolated LAI values are obtained at a certain moment in time and consequently, continuous monitoring is not feasible. Finally, it is not desirable to have a destructive method in place for monitoring the LAI values since the canopy of the VGS must be preserved. Therefore, indirect methods, discussed in the next section, are more suitable. Still, the destructive leaf harvesting method could be helpful as a calibration method to validate the indirect methods or new techniques.

### 5.1.3 Indirect methods for LAI measurements

#### 5.1.3.1 Radiative transfer theory

The most widely used and the longest established indirect technique for determining the LAI measures the transmission of light radiation through the canopy [21,22,25,27,55]. This technique is referred to throughout this paper as the ‘radiation transfer theory’ technique. There are two approaches for measuring the radiation transfer through the canopy [55]: 1) the radiation measurement approach which measures the attenuation of irradiation with depth in the canopy; and 2) the ‘gap-fraction’ approach which measures the fraction of sky that is visible through the canopy and includes all gaps observed from a single point with some angular view range, assuming randomly distributed leaves [21,25,56].

In the radiation measurement approach, the LAI is calculated by transforming the Beer-Lambert law (Equation 4). This law considers the radiation intercepted by the canopy and depends on the canopy structure. The photosynthetically active radiation (PAR), i.e. radiation in wavelengths of 400 to 700 nm, below and the light above the canopy, or in front and behind the canopy, are measured. A high transmission value ($Q_i$) corresponds to a thin and open canopy, while lower values correspond to more dense canopies [35]. The canopy extinction coefficient k determines how strongly an object absorbs light and is dependent on the leaf-angle distribution and the angle of the incident light, or zenith angle [11,21,35].

$$Q_i = Q_0 \, e^{-k \, LAI} \tag{4}$$

| | |
|---|---|
| $Q_i$ | Light below canopy |
| $Q_0$ | Light above canopy |
| k | Canopy extinction coefficient |
| LAI | Leaf Area Index |

In VGS the radiation measurement approach, or PAR measurement, is frequently used for obtaining LAI values of green facades (cf. Table 1) [11,16,35,48,53]. PAR measurements are done with a ceptometer. Light measurements in front and behind the canopy need to be performed in identical weather conditions, preferably during overcast conditions as this will avoid having to make assumptions about the sun's elevation angle [16,35]. The formulas used for deriving the LAI from PAR measurements are described in the Appendix (cf. Section 8).

Pérez et al. [35] used a PAR Sunfleck Ceptometer for determining the LAI values of a DSGF in Summer. In total 10 PAR, light repetitions were recorded behind the canopy ($Q_i$), in three different orientations (South, East, and West) and at 3 height levels (upper, middle, and lower) to capture the spatial variability within the canopy. The radiation measurements in front of the canopy ($Q_0$) were made under the same light conditions as behind the canopy, on a cloudy day in Summer. The LAI values were then calculated by using Equation A.3. The LAI values of the DSGF ranged between 0.8 and 3.9. The LAI values of the East facade were higher compared to the South and West facades since the plants at these orientations were replanted. At the west facade, the effect of mature leaves and young leaves was obvious, the LAI on the lower level was on average 3.1, while on the higher level the LAI was only 1.1. From this research, it was concluded that a completely developed Boston ivy (*Parthenocissus tricuspidata*) canopy under a Mediterranean continental climate can achieve LAI values that range between 3.5 and 4.

Vox et al. [48] and Pérez et al. [16] used the AccuPAR PAR/LAI Ceptometer (model LP-80, Decagon Devices Inc., Pullman, WA, USA) to measure PAR radiation to determine the LAI of a DSGF. Pérez et al. [16] used this method as a validation for the NDVI technique (cf. section 5.1.3.2). However, in both studies, no more information is given about the frequency and location of the measurements. Vox et al. [48] provided measurements on two DSGF, for *Rhyncospermum jasminoides* LAI values between 2 and 4 were measured and for *Pandorea jasminoides variegated* LAI values between 1.5 and 3.5. The methodology for obtaining the LAI values was not mentioned.

The devices used by Convertino et al. [11] and Bakhshoodeh et al. [53] for measuring PAR radiation are not further specified. Bakhshooded et al. [53] did 20 light measurements on two different north and west-oriented DSGF. The LAI of *Wisteria sinensis* ranged between 1.6 and 3.5, and an average value of 2.7 (±0.6) was calculated using Equation A.2. The *Hibbertia Scandens* ranged between 0.9 and 3.5 with an average value of 2.3 (±0.8). Convertino et al. [11] performed light measurements on five consecutive days in September for two different solar angles ($\theta = 90°$ and $\theta = 70°$) on a South-oriented facade with *Rhyncospermum jasminoides*. An average value LAI value of 2.2 and 2.65 was obtained. The LAI values were calculated using Equation A.2.

In the gap fraction approach, gap fractions of diffuse radiation transmission through the canopy in a range of zenith angles are measured by plant canopy analyzers [55]. A frequently used plant canopy analyzer is the Li-Cor LAI-2200C plant canopy analyzer. The LAI-2200C plant canopy analyzer measures the interception of blue light (320 – 490 nm) at five zenith angles and requires above and below readings [57].

In all the studies mentioned below the Li-Cor LAI-2200C plant canopy analyzer was used to measure the LAI. Šuklje et al. [47] measured the LAI in two types of VGS, a one-layer DSGF and a two-layered DSGF with *Phaseolus vulgaris L*. The measurements were done in 10 points of the same height at the beginning, middle, and end of the testing period. An average LAI value was obtained of 6.1 (±0.5) for the one-layer facade and 7.2 (±0.6) for the two-layer facade. Zhang et al. [51] measured the LAI of a DSGF vegetated with orange trumpet vine (*Pyrostegia* *venusta*) on three consecutive days. The 3-day mean of the LAI was 4.51 (±0.033). Lin et al. [54] reported LAI values between 1.56 – 3.61 for a DSGF. There are no further specifications on the measurements, plant species, or facade design.

### 5.1.3.2 Normalized Difference Vegetation Index (NDVI) technique

The Normalized Difference Vegetation Index technique (NDVI) to determine the LAI relies on measuring the ratio of light reflected in the optical spectrum, more specifically in the red waveband (ca. 700 nm) and in the near-infrared (NIR) spectrum (ca. 900 nm). This ratio can be expressed in a vegetation index, the NDVI, by Equation 5.

$$\mathrm{NDVI}= \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + \rho_{red}} \tag{5}$$

$\rho_{red}$ Reflectance in red waveband
$\rho_{NIR}$ Reflectance in NIR waveband

Chlorophyll, present in green healthy plant leaves, absorbs much of the radiation in the red waveband (wavelength of ca. 700 nm). A plant’s spongy mesophyll (cell structure) layer typically causes high reflectance values in the NIR waveband. The NDVI can therefore be used as an indicator of vegetation density [21,58]. As the LAI of a canopy increases, the chlorophyll content in the canopy will also increase, resulting in an increased absorption in the red waveband. On the other hand, the NIR reflectance increases due to the expanding mesophyll in the canopy. An increase in LAI will therefore result in an increasing NDVI value [16].

The NDVI technique was first demonstrated in VGS by Pérez et al. [16] on a DSGF vegetated with Boston ivy (*Parthenocissus tricuspidata*) in three orientations. To monitor the NDVI values of the green facade, SRS-NDVI (spectral reflectance sensors) sensors were installed permanently on the facade at an appropriate height and distance away from the facade to capture the entire surface. The NDVI sensors were mounted on a tripod and placed in front of the facade. In total, four different sensors were installed with different viewing angles, one with a hemispherical view and three other sensors with a 36° field of view. Since the LAI and NDVI do not show a unified relationship, as other factors like diseases, water stress, mineral deficiency, etc. may also influence the NDVI values, a site-specific correlation between the LAI and NDVI needed to be developed [21,59,60]. The manual LAI values were determined with a ceptometer, AccuPAR LP-80 Decagon, during moments of rapid foliar changes (i.e. in spring and fall). Next, a linear model was developed using a least-squares regression to correlate NDVI values with manually determined LAI values. The results showed a high correlation of $r^2 = 0.94$ between NDVI and LAI measurements. The LAI was measured for an uninterrupted period of one year and seven months. Five different periods were distinguished with accompanying LAI values: early summer (full new leaf), late summer (degraded foliage), autumn (fall), winter (no leaves), and spring (growth). The LAI values varied due to seasonality and facade orientation. A range of LAI values between 0.9 and 4.8 over the seasons was reported.

## 5.2 Principles of indirect LAI measurement techniques used outside the domain of VGS

In other domains (e.g., agriculture and forestry), research on indirect camera-based techniques determining LAI values is more advanced. By evaluating these techniques, we can assess if they could be applied in the domain of VGS. The next section will elaborate on the most relevant techniques used in these research domains. In the discussion, it is argued whether these techniques can be applied to VGS or what prevents an easy 1-to-1 transfer.

### 5.2.1 Smartphone camera – digital image analysis

The use of smartphones for determining vegetation characteristics in agriculture or forestry has been intensively explored over recent years [61–66]. Several smartphone applications were developed for determining LAI values, such as PocketLAI for measuring LAI values of trees by Orlando et al. [61] and VitiCanopy for measuring LAI values in grapevines by De Bei et al. [66]. The possibility of using a smartphone makes it more accessible and low-cost for e.g., farmers to measure crop performance without the need for the use of destructive harvesting methods, which are time-consuming, or more expensive devices such as plant canopy analyzers [65].

VitiCanopy uses a smartphone front camera and built-in GPS capabilities to automatically implement image analysis algorithms on upward-looking digital images of canopies [66,67]. The algorithms are developed using digital image analysis and MATLAB programming and are based on gap analysis and transmission of light through the canopy based on Beer's law (Equation 3). The images are usually taken from a distance, for example, 80 cm, below the grapevine canopy. The application can be used in all weather conditions. PocketLAI operates similarly. The LAI estimates are based on real-time image processing based on an automatic segmentation algorithm to derive gap fraction and the LAI [61]. The images are taken at a 57° angle below the canopy of the tree. In general, both applications perform well, with a correlation of $r^2 = 0.95$ between VitiCanopy and the LAI measured with the LAI-2000 plant canopy analyzer and an overall correlation of $r^2 = 0.78$ between PocketLAI and LAI obtained from hemispherical photography in broad-leaf shrubs and trees.

### 5.2.2 3D point clouds

The use of 3D images, or 3D point clouds, of canopies for deriving LAI values is already tested in other research domains and can be achieved by various instruments or cameras. A commonly used instrument is a Light Detection and Ranging instrument (LiDAR). This instrument sends out light pulses in a narrow beam of coherent light, in a precise waveband and the reflected signal is received back at the instrument. The time delay of reflected pulses is used to determine an estimate of the distance between the sensor and the object [21]. LiDAR scanners can be classified according to the platform they are mounted on, i.e. Spaceborne Laser Scanners (SLS), Airborne Laser Scanners (ALS), Terrestrial Laser Scanners (TLS). Wang et al. [68] did a review on the use of LiDAR technology for deriving the LAI in forests. Mainly, the LAI is estimated using the correlation between the gap fraction and the contact frequency, defined as the probability of a beam penetrating the canopy and coming into contact with a vegetative element. LAI is also estimated based on the regression of forest biophysical parameters derived from LiDAR (i.e. height and foliage density metrics). Indirabai et al. [69] developed an algorithm for deriving the LAI in forests that established a relationship between TLS point density, point spacing, and the height of trees. LAI values were validated using an LAI-2200C plant canopy analyzer and a consistent correlation of $r^2=0.96$ was found. Although the use of 3D point clouds for determining the LAI of VGS is an unexplored research area, LiDAR technology has been used in the field of VGS by Pérez et al. [70] for measuring the vegetation volume of a green facade. According to Pérez et al. [70], combining the 3D model of the green facade and including analytic properties like LAI could lead to better modeling of the benefits such as thermal and acoustic performance. In this research, a Mobile Terrestrial Laser Scanner was used and mounted on a vehicle. The laser scanner performs 40 scans per second in a vertical plane perpendicular to the direction of movement. The measurements were performed at a distance of ca. 4.5 m parallel to the facade.

Time-of-flight (ToF) cameras follow a similar principle, the object is illuminated with a light source and the reflected light is observed by the camera. The phase shift between the illuminated light and the reflection is measured from which the distance is calculated. Vasquez-Arellano et al. [71] mounted the Kinect V2 camera on a robotic platform to acquire 3D data on maize plants for estimating the leaf area. The ToF camera was mounted on a robotic platform at a height of 0.94 m with a downward angle of 45°. The platform moved parallel to the maize plants. By using different scan directions, point clouds from different 3D perspective views were merged. For estimating the leaf area, a methodology was proposed for reconstructing the surface of a rasterized point cloud after alignment and merge. A mean error of 8.8%, 7.8%, and 32.3% was found depending on the different point cloud reconstruction methods.

Stereo vision is another technique used for the 3D characterization of objects. Two (or more) cameras are used to view the same object. This can be compared to how depth vision is obtained by binocular vision (i.e., human vision). Leemans et al. [72] estimated the LAI of a wheat crop using two identical twin-colour CMOS cameras. The cameras were set at a distance of 115 mm at a downward-looking position. Leaf areas were measured using pixel recognition algorithms and the ground area was estimated based on the mean distance from the leaves to the camera. The obtained LAI from the 3D image showed a high correlation with the reference measurements obtained by destructive leaf harvesting. The LAI values could be measured with an average standard deviation of 0.39.

In photogrammetry, multiple images at different angles are taken. The images overlap and a 3D image is established. This is often obtained by Unmanned Aerial Vehicles (UAVs). In research conducted by Comba et al. [73] and Li et al. [74], the use of 3D point clouds from UAV imagery was evaluated as an alternative to traditional LAI measurements, in vineyards and for maize crops, respectively. In both studies, a multivariate regression model based on canopy descriptors derived from the 3D point cloud, i.e. leaf density distribution, canopy thickness, and height, was established for deriving LAI values. Comba et al. [73] found a correlation of $r^2=0.82$ between the LAI values derived from the 3D point clouds and LAI obtained from the destructive leaf harvesting method. On the other hand, Li et al. [74] found a less desirable correlation of $r^2=0.48$ between the LAI values from the 3D point clouds and the validated LAI values, obtained with a ceptometer. The reason for this low correlation is explained by the lower point density values caused by missing maize plants in the sampled area leading to an inaccurate estimation of canopy density and LAI.

### 5.2.3 RGB and multispectral camera system

Research by Fan et al. [75] explored the use of a visible and near-infrared (V-NIR) camera system for monitoring the LAI of ryegrass. The camera’s spectral responses in the three bands are 520-600 nm (green), 600-780 nm (red), and 780-1000 nm (NIR). The camera was mounted on a tripod at the nadir position (downward view) at 2.5 m above the grass. Radiometric calibration was performed to convert the digital images into radiometric images. This is necessary so that every pixel represents light measurements. As crop growth model, the four-parameter logistic model (4PLM), was used to fit the in-field-measured LAI. The predicted LAI and the measured LAI have a correlation of $r^2 = 0.79$.

LAI values determined with satellite data correspond to the total green LAI of all the canopy layers and represent global LAI retrievals [26]. Various models used in agriculture, ecology, carbon cycling, and climate studies use the LAI to quantify the amount of leaf material that is present. LAI retrievals are obtained with the satellites PROBA-V, Sentinel-2, and SPOT-4 & 5 [26]. The reflectance values are obtained in the blue, red, and NIR spectral bands. These reflectance values are input into the neural networks to retrieve daily estimates of LAI at a spatial resolution of 300 m [76]. In machine learning algorithms, LAI-related data such as vegetation indices, color indices, reflectance, and texture index are extracted from the images and used as input data for improving LAI predictions [77].

## 6. Discussion

As explained in the previous section, some indirect techniques are already used to determine LAI in VGS. However, these techniques are not adapted to vertical greening systems. In forestry and agriculture, the techniques used for LAI monitoring are often more developed, designed, and standardized to the specific application. To take steps forward towards dedicated techniques for LAI monitoring in VGS, this chapter will evaluate the techniques presented in section 5 and assess their applicability to VGS. Furthermore, current shortcomings in determining and reporting LAI values in VGS applications will be presented. Finally, recommendations for uniform and robust LAI determination and improved - standardized - LAI reporting will be presented.

## 6.1 Evaluation of LAI monitoring techniques

### 6.1.1 The radiative transfer theory

The radiative transfer theory technique is the most used indirect technique for obtaining LAI values both inside and outside the domain of VGS. Although not yet tested on LWS and TSF, this technique should apply to any VGS type. The main limitation of this technique is that it is necessary to sample at several locations to obtain reliable results since radiation levels can vary from full sun to almost zero over a few centimeters [16,27,35]. Pérez et al. [35] conducted 10 repetitions of light measurements at six different locations distributed across the canopy while in the remaining studies listed in Table 1 often only one measurement was performed. This makes the LAI measurements less robust and less representative of the entire canopy. This problem will be even greater in LWS, where many different plant species are used, compared to a homogeneous canopy. A second limitation of this technique is that in dense canopies, i.e. high LAI values, it becomes more difficult to observe variations in LAI values as little light can penetrate through the canopy and little light is left to be measured by the ceptometer or plant canopy analyzer [35]. The third limitation is that often an underestimation in LAI values is reported when applying Beer's law. Convertino et al. [11] reported that LAI values measured with the indirect method were 46.5% and 35.5% lower (at $\theta=90°$ and $\theta=70°$ respectively) than the LAI values determined with the destructive leaf harvesting method. This underestimation is also commonly reported in horizontal crops. Various studies report that the reason for this underestimation lies in the non-random distribution of foliar elements within the canopy [27,78]. This shows the importance of sampling with multiple repetitions at different locations within the canopy. Another disadvantage is that in this method, it could be difficult to distinguish radiation intercepted by leaves or woody tissue, such as stems and branches, of the canopy [21]. An approach to overcome this issue is to include red and NIR band camera systems so that the reflective properties of the woody material can be distinguished from the leaf material [21].

The practical issue with using this technique is that the measurements with the ceptometer or plant canopy analyzers are done manually. This makes that measurements can only be performed at an accessible height, ca. two meters above the ground surface. In reality, VGS are usually higher than that. Getting a complete picture of the foliage is therefore not possible using this technique without expensive lift or racking equipment.

### 6.1.2 NDVI technique and V-NIR camera system

The advantage of techniques relying on spectral properties of the canopy such as the NDVI technique and the V-NIR system proposed in agriculture is that leaves and woody materials can be distinguished more easily because they have different spectral properties. Also using spectral properties, no assumptions must be made on the leaf angle distribution or solar zenith angle which is the case in the radiative transfer theory technique. The NDVI technique proposed by Pérez et al. [16] for estimating LAI values showed promising results for DSGF. This technique does require a site-specific correlative relationship between the LAI and the NDVI values since NDVI can correspond to multiple LAI values. Pérez et al. [16] measured LAI values with the AccuPAR ceptometer. Outside the domain of VGS, the relationship between LAI values and NDVI values has been explored extensively. The main issue with the determination of the relationship is that at high LAI values, the NDVI becomes less sensitive to LAI changes [60,79]. Literature indicates that the NDVI is most sensitive to LAI values between 0 and 4.0 [80]. Although a high correlation is found between the NDVI and LAI by Pérez et al. [16], it must be noted that the measured NDVI values at high LAI values deviated more from the fitted curve, compared to low LAI values, meaning that the results are less robust at higher LAI values. A practical drawback to this technique is the need for a support structure to place the sensors at a certain distance from the facade [16].

In LWS the NDVI technique is not yet tested. In the case of LWS, some important issues must be considered. LWS consist of both a substrate and vegetation. The substrate in some cases consists of organic material (e.g., moss). In this case, the substrate can affect the reflectance properties of the system, especially in case of low vegetation cover when the substrate is exposed. This is because the organic material, or moss, also sends out reflective properties. Moss tends to have a lower reflectance in the red and NIR wavebands compared to green vegetation [81]. However, this reflectance will contribute to the reflectance of the vegetation which may result in an overestimation of LAI values. The wetness of the substrate will affect the spectral reflectance properties and influence the LAI values [82]. These effects (reflectance and wetness of the substrate) will only affect the NDVI values, or general spectral properties in case of low vegetation coverage (i.e., coverage<100% or LAI<1) when the substrate layer is exposed.

### 6.1.3 Smartphone camera – digital image analysis

Although this technique has great application potential in the field of agriculture and forestry, the properties of VGS prevent its broader use in this sector. This technique relies on measuring the gap fraction behind the canopy at a certain distance away from the foliage. In VitiCanopy, a distance of 80 cm is used and in PocketLAI photos need to be taken at a specific angle and distance below the canopy. In VGS it is not possible to do these measurements at a distance behind the canopy, especially in LWS and TSF since there is no space behind the canopy. In the case of DSGF, a gap between the wall and the vegetation is present, however often only a few centimeters.

### 6.1.4 3D point clouds

A major advantage in determining the LAI from 3D leaf geometry images is that there are no assumptions needed on the leaf angle distribution of the canopy or the solar zenith angle, as opposed to the radiative transfer theory technique [72]. Not working with light transmission through the canopy or light reflectance values, which may be susceptible to local differences, makes this technique more robust to the spatial variability within the canopy. Both the radiative transfer technique and the NDVI technique reported that at high LAI values, the techniques become less sensitive to LAI changes [35,60,79,80]. Since LiDAR technology uses very narrow beams of light that penetrate through the gaps in between leaves, i.e. an active form of remote sensing technology, it can alleviate the saturation problem at high LAI values because of the direct determination of the canopy structure [68].

Although it is expected that by using 3D point clouds in VGS it should be possible to determine LAI, some issues do need attention. First of all, previous research used sets of the canopy and forest descriptors for establishing a relationship between the 3D point cloud and LAI [68,69,73,74], for example, the leaf density distribution, canopy thickness, and tree height. In the case of VGS, similar boundary conditions for the canopy should be established. What these boundary conditions should be needs further investigation. Secondly, when using time-of-flight cameras like the Kinect V2, it is reported that the quality of the depth data is inversely related to the distance between the object and the camera. Moreover, measurements should be taken close to the canopy for obtaining detailed data on leaf geometry and consequently the leaf area [83]. This could be an obstacle in VGS because in this case, the camera will also need to be able to measure vertically, and not only horizontally such as in agriculture. Practically, this will be more difficult to realize.

### 6.1.5 Summary of LAI determining techniques inside and outside the domain of VGS

Table 2 gives a summary of the currently available techniques for LAI determination inside and outside the domain of VGS. The table lists the different techniques along with the studies in which they were used. The advantages and shortcomings of each technique are also briefly mentioned.

*Table 2: Overview of existing indirect techniques for LAI determination in VGS and other domains*

| | **Studies** | **Advantages** | **Shortcomings** |
|---|---|---|---|
| **Techniques used in VGS** | | | |
| **Radiative transfer theory** | Wong et al. (2009) [15]<br>Šuklje et al. (2016) [47]<br>Pérez et al. (2017) [35]<br>Vox et al. (2018) [48]<br>Zhang et al. (2019) [51]<br>Convertino et al. (2021) [11]<br>Pérez et al. (2022) [16]<br>Bakhshoodeh et al. (2022) [53]<br>Lin et al. (2022) [54] | - Easy to use<br>- Quick measurements | - Many measurements needed to capture spatial variability within canopy<br>- At high LAI values, measurements are less reliable<br>- Underestimation in LAI values reported due to non-random distribution of foliar elements<br>- Manual measurements only possible to certain height |
| **NDVI technique** | Pérez et al. (2022) [16] | - Leaves and woody material can be distinguished<br>- No assumptions must be made on leaf angle distribution or solar zenith angle<br>- Continuous LAI measurements<br>- Spatial variability within canopy is captured | - At high LAI values (LAI > 4), NDVI becomes less sensitive to LAI changes<br>- Not tested in LWS, BUT spectral properties of the organic material of the substrate (e.g. moss) might interfere with NDVI values |
| **Techniques used outside the domain of VGS** | | | |
| **Smartphone camera – digital image analysis** | Orlando et al. (2015) [61]<br>De Bei et al. (2016) [66] | - Measurements with smartphone apps are easy to use | - Measurements need to be done at certain distance behind the canopy; this is not possible in VGS |
| **3D point clouds** | Indirabai et al. (2020) [69]<br>Vasquez-Arellano et al. (2018) [71]<br>Leemans et al. (2013) [72]<br>Comba et al. (2020) [73]<br>Li et al. (2022) [74] | - No assumptions must be made on leaf angle distribution or solar zenith angle<br>- LiDAR could alleviate the saturation problem at high LAI values | - Boundary conditions need to be established<br>- Quality of depth data with time-of-flight cameras is inversely related to distance<br>- Measurements need to be taken close to the canopy which is difficult in case of VGS |
| **V-NIR camera system** | Fan et al. (2018) [75] | - Leaves and woody material can be distinguished<br>- No assumptions must be made on leaf angle distribution or solar zenith angle | - Boundary conditions need to be established<br>- Establishing vegetation growth model that can fit the measured LAI values |

## 6.2 Current shortcomings in determining and reporting the LAI of VGS

When analyzing the studies that reported on LAI in VGS (cf. Table 1), shortcomings in determining and reporting the LAI values were encountered. First of all, in many studies only one LAI measurement was done, and that LAI value was taken as the value for the entire facade. When doing measurements based on the radiative transfer technique and destructive leaf harvesting method, spatial variability within the canopy must be taken into account by sampling at different locations in the canopy. Secondly, the dynamic value of the parameter is often overlooked. The LAI is not a static value as it changes according to external influences, such as seasonality and facade orientation [14,30,35]. Only one study measured LAI values over a longer period. Pérez et al. [16] studied the effect of seasonality and LAI values of a Boston ivy DSGF on energy consumption throughout the year in a Mediterranean continental climate (Csa). The DSGF provided energy savings for cooling up to 54% in early summer and 30% during late summer. However, during the leaf-off stage, the energy consumption increased by 5.4% in autumn and winter due to the presence of branches which lowers the solar radiation on the wall in winter and causes the building to heat up more slowly. Thirdly, the reported LAI values consistently give too little information on the boundary conditions at the time of LAI determination. Many studies did not provide sufficient information on e.g. plant species, the device used for measurements, and facade orientation. This makes it difficult to generalize these values into tabulated reference data for performance predictions. Lastly, in previous studies, LAI values of facades with mostly only one plant species and a homogenous canopy are considered. LAI data on mixed canopies with multiple plant species (i.e. LWS) are currently missing. The only used technique in LWS for LAI determination is the destructive leaf harvesting method. A proper indirect technique is missing or not yet tested.

In summary, to date, there is consistently not enough data available on the LAI in VGS. This complicates calculating the benefits that VGS provide. The main reason for this is the lack of a proper LAI monitoring method and the lack of a robust sampling protocol. The following section proposes guidelines that address how LAI values could be reported and measured in VGS with the currently available techniques.

### 6.3 Recommendations for uniform and robust LAI determination and reporting

Based on the identified shortcomings in LAI determination and reporting, the following recommendations are made and translated into good practice guidelines. Figure 5 summarizes the most important steps needed in the determination and reporting of LAI values in VGS. This is an initial proposal for good practice guidelines, which can be further optimized in future research. An explanation of these guidelines is given below.

First of all, even when research is not specifically about LAI, sufficient information should be provided on the source of LAI data or the method used to determine the LAI. This is often given far too little attention. The methodology and devices used should be documented, as should the number of measurements carried out, the time and date of the measurements, the location of measurement points, and the dimensions of measurement areas. In addition, it should be explained how the measurement data were processed. Without this, reporting single-value LAI data is of limited value.

Related to this is a need to consistently provide more information on the boundary conditions during LAI determination. Boundary conditions that should at least be mentioned because they are readily available are VGS type, canopy specifications (mixed/homogeneous canopy, deciduous/evergreen), plant species, facade orientation, and climate type. They can be complemented by other more specific factors influencing LAI that require a little more work to establish, such as soil type or water availability. Consistently giving a more detailed description of the methodology used and the boundary conditions will make it easier to provide reliable tabulated LAI values. These are of crucial importance in estimating/calculating the benefits of VGS e.g. for calculating the cooling potential of VGS. Working in such a standardized way, viz. working with a checklist of minimum information to be reported, would allow the setting up of a database with well-defined LAI values for specific conditions of VGS, which would be very valuable both from a research perspective and for practice.

Secondly, when determining the LAI values of the facade manually i.e. with ceptometers, plant canopy analyzers, or in a destructive manner, it is crucial to capture the spatial variation within the canopy. Pérez et al. [35] found that when sampling the green facade, a large difference was observed between LAI values at the top and bottom of the facade, due to the leaves at the bottom being older than leaves more at the top, which is commonly the case with climbing plants. It is therefore recommended to subdivide the green facade into smaller plots, for example, 1m x 1m, or $1m^2$, and determine the LAI on a plot level. Here, it is important that especially the vertical direction is considered. Afterward, an average value can be provided for the entire canopy. When the LAI is determined with a ceptometer or plant canopy analyzer, it must be taken into account that light intensities behind the canopy can vary greatly over a small distance. Therefore, it is important to perform several measurements within a plot until a stable LAI value is obtained.

A last important point to consider is the dynamic nature of the parameter. If the study allows it, it is strongly recommended to measure the LAI frequently. Seasonality, in temperate climates, can greatly influence the LAI. When for example simulating energy savings from the cooling process that VGS provides throughout the year, it is important to consider the effect on energy consumption in other seasons [16].

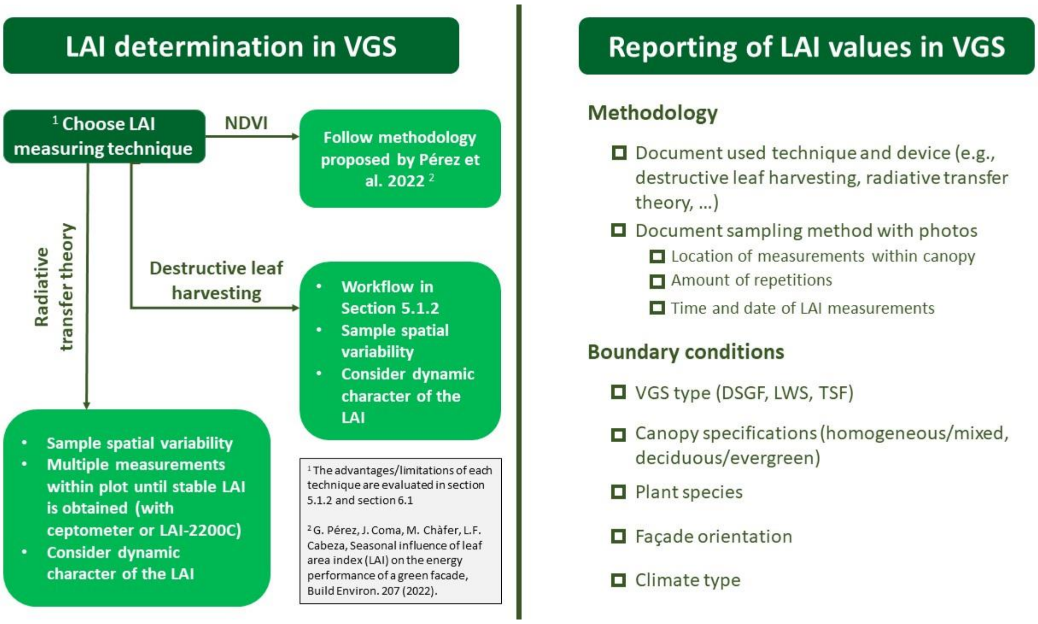

*Figure 5: Overview of proposed guidelines for LAI determination and reporting of LAI values in VGS.*

## 7. Conclusion and recommendations for future research

LAI provides information on the total leaf area in a VGS canopy and is directly linked to the magnitude of the various benefits provided by VGS. Therefore, LAI is considered a key performance indicator of vertical greening. Proper characterization of this index is therefore crucial for understanding Vertical Greening Systems, predicting their performance, and improving their use. Yet in the field of VGS, comprehensive datasets on LAI data are lacking under various boundary conditions, reporting on LAI is often inadequate and non-standardized, and specific monitoring techniques for LAI are absent. In this context, this paper aimed to expose the problems, define the research gaps and seek answers regarding the use and monitoring techniques for LAI determination and reporting in VGS.

It was elaborated that currently, the most widely used techniques for LAI determination in VGS are radiative transfer theory and the destructive leaf harvesting method. Nevertheless, the way these techniques are currently used is often problematic. It could be observed that they are sensitive to changes in LAI within the canopy. Therefore, without a proper sampling method, which is often the case, isolated LAI values are obtained that are not representative of the whole canopy. A newer technique that seems to offer more possibilities is based on NDVI measurements. This technique allows continuous LAI values to be obtained over a longer period, making it more robust and promising for continuous LAI monitoring. It was also noted that there is much to learn from other research areas, where much more developed techniques for LAI determination were observed and adapted to each specific domain. For example, the use of 3D point clouds is a technique that is currently completely unexplored in the VGS domain but could contribute to specific LAI determination using digital imaging.

Finally, a clear need for standardized reporting of LAI was identified. In this regard, guidelines were drafted and presented schematically. These are by no means a fixed framework, but rather a proposal submitted to the scientific community to initiate a debate.

Through this broad analysis, we hope that researchers better understand the importance of the LAI and the importance of its proper characterization and reporting. We also hope to have clarified the need for specific monitoring techniques and the importance of standardized characterization. Future research could focus on how existing and new techniques can be combined and/or adapted to the peculiarities of VGS to enable a better, more robust, and continuous characterization of the parameter and establish LAI databases for both research and practice. Furthermore, LAI determination techniques could be extended further to include health determination of the canopy to optimize the maintenance of VGS systems to avoid excessive maintenance costs.

## Acknowledgments

**Funding**: This work was conducted within the framework of the practice-oriented research project "WonderWalls", supported by Flanders Innovation and Entrepreneurship (VLAIO) under the TETRA funding program [HBC.2020.2102].

# 8. Appendix

## List of abbreviations

| | |
|---|---|
| BGS | Building-related Greenery Solutions |
| DSGF | Double-Skin Green Facade |
| GF | Green Facades |
| LAI | Leaf Area Index |
| LAD | Leaf Area Density |
| LiDAR | Light Detection and Ranging |
| LWIR | Longwave infrared |
| LWS | Living Wall Systems |
| NDVI | Normalized Difference Vegetation Index |
| NIR | Near Infrared |
| PAR | Photosynthetically Active Radiation |
| PM | Particulate Matter |
| TLS | Terrestrial LiDAR Scanner |
| TSF | Traditional Skin Facade |
| UAV | Unmanned Aerial Vehicles |
| VGS | Vertical Greening Systems |
| V-NIR | Visible and Near Infrared |
| WLAI | Wall Leaf Area Index |

## LAI calculation from PAR measurements

The LAI calculations from light measurements are based on Beer's Law (Equation 4). From this equation, the extinction coefficient is formulated as [35]:

$$k = \frac{\sqrt{\chi^2 + \tan\theta^2}}{\chi + 1.744(\chi + 1.182)^{-0.733}} \tag{A.1}$$

Θ is the solar zenith angle, χ is the leaf angle distribution. This describes the projection of the leave area in the horizontal plane, where $\chi < 1$ represents canopies with predominately vertical orientations and $\chi > 1$ canopies with predominately horizontal orientations and $\chi = 1$ in mixed orientations.

The LAI is calculated as:

$$LAI = \frac{\left[\left(1 - \frac{1}{2k}\right) f_b - 1\right] \ln \tau}{A(1 - 047 f_b)} \tag{A.2}$$

Where A is the leaf absorptivity with a value of 0.9 for most of healthy green foliage, $f_b$ is the beam fraction which is calculated as the ratio between diffuse (scattered in the atmosphere) and beam radiation (direct from the sun), τ is the ratio transmitted PAR and incident PAR above the canopy. In overcast days $f_b = 0$. Equation A.2 can be simplified into following equation:

$$LAI = \frac{-\ln\left(\frac{PAR_{below}}{PAR_{\ above}}\right)}{0.9} \tag{A.3}$$

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