CITIESALIVE
16TH ANNUAL GREEN ROOF & WALL CONFERENCE
NYC | SEPTEMBER 24-28, 2018

Session Number: Session Title

TRANSMISSIVITY OF VINING GREEN WALLS; EVALUATION OF EXTINCTION COEFFICIENT FOR VARIOUS GEOGRAPHICAL LOCATIONS

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Abstract

Indirect vining green walls are a particularly promising component of green infrastructure. Compared to living walls, they are cost effective, and, if designed properly, require minimal human intervention and maintenance over their lifespans.

Indirect vining green walls negate the Urban Heat Island Effect and reduce the cooling loads of buildings through solar interception and transpiration. However, the lack of an effective methodology for evaluating the performance of various green wall designs in different climates has hindered their uptake as a passive design strategy.

A key variable impacting both solar interception and transpiration is the extinction coefficient (k). This is a dimensionless variable describing the ratio of shadow area to actual leaf area. With a few exceptions, most studies on green walls use a generic k value. This approach disregards canopy characteristics and site location.

This study provides a novel methodology for estimating the average monthly k values for vining green wall canopies in different latitudes during the summer. This is done by evaluating both values obtained from statistical models and empirical measurements from grapevine trellis systems with canopy geometries similar to those of vining green walls. This study shows that for the latitudes less than or equal to 32°, and greater than or equal to 44°, k values of 0.5 and 0.6 should be used, respectively.

Introduction

Green walls are a component of urban green infrastructure. They can be categorized into three main types: living walls, direct green walls, and indirect green walls [1-3]. Living walls are a relatively new design solution. They consist of plants hosted in artificial substrates. Hydroponic technology is used for irrigation and nutrient diffusion.

Direct green walls utilize clinging climbers—plants with adventitious roots and adhesive disk tendrils—to create a vegetative surface [4]. They are the least costly of the three systems because they are supported by buildings. However, the aggressive nature of the vines limits the usefulness of direct green walls to masonry buildings.

Indirect green walls also use vines. These systems utilize climbing vines such as twining plants, leaf climbers, and tendril bearers, and provide independent structures to support the vegetative canopy [1]. Because the support structure is affixed to a building façade, indirect green walls can be used for different building construction types.

Furthermore, the geometry of the vegetative canopy of an indirect green wall can be adjusted to control the thermal performance of the overall structure [5]. Thus, indirect green walls provide a robust design system. During the summer, they reduce the solar heat gain of buildings by intercepting solar radiation [6-11]. Green walls also reduce building infiltration rates by reducing natural and forced convection flows. They create an insulating air layer between the façade and the vegetative layer [2,12,13] and cool the microclimates around buildings via evapotranspiration [14-18].

The extinction coefficient, *k*, is an important variable, as it impacts the cooling effects from both shading and transpiration [19-21]. It defines the statistical probability of a solar ray passing through a canopy [19]. Depending on the wall construction type, the shading effect contributes the most to the cooling impact of green walls on buildings [13,22]. The magnitude of this cooling depends on the geometry and orientation of the green wall canopy [1,18,23].

Of the total net solar radiation received by green walls, some is transmitted through the leaves and canopy, some is reflected, and a small portion is absorbed for photosynthesis processes [19]. The amount of solar irradiance passing through a canopy, i.e., the shading effect, is directly related to the value of the extinction coefficient [19].

Similarly, the transpiration rate of a canopy is a function of the extinction coefficient value [24]. That is because the canopy transpiration rate is directly related to the total solar radiation received by a canopy. However, despite the significant influence of the extinction coefficient on the cooling performance of green walls, thus far, limited investigations have been conducted to determine the best range of values of *k* [5,11].

By contrast, in the fields of agronomy and plant biophysics, much work has been done to evaluate the extinction coefficients of grapevine trellis systems through both theoretical and empirical methods. Since the extinction coefficient value is a function of the geometry of a canopy, these investigations, if translated properly, can serve as a great source of information to evaluate *k* values for green walls.

The goal of this study is to establish a range of extinction coefficient values for vining green walls. To that end, first, two theoretical methods for estimating extinction coefficient values are introduced and evaluated. Second, extinction coefficient values obtained from empirical studies of both vining green walls and grapevine canopies with geometries similar to those of green walls are reviewed. Lastly, the findings from the theoretical and empirical methods are compared to identify the best range of values for the extinction coefficients of vining green walls.

Statistical Method Defining Extinction Coefficient (*k*)

The extinction coefficient, *k*, defines the ratio of the shadow area to the actual leaf area [19]. It is a function of solar elevation, β, and leaf orientation. Leaf orientation is described by the angle between the zenith and the projection normal to the leaf surface, α, and the difference between leaf and sun azimuth angles, θ (Figure 1) [25].

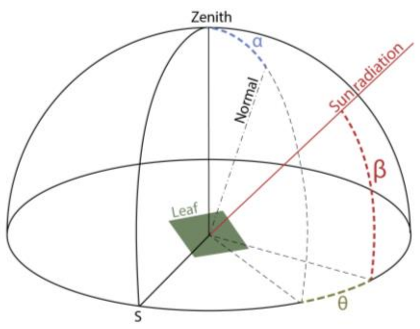


Figure 1. A leaf orientation defined in a spherical system coordinate. S: South, β: Solar altitude angle, α: the angle between a projection normal to the leaf surface and the zenith, which is equal to the angle between the leaf and the horizon, θ: the azimuth difference between the leaf and

Table 1 provides simplified equations for different leaf inclinations as a function of solar elevation, β [19]. The particular arrangement of leaves within a green wall canopy is highly dependent on its support structure design and the selected vine species. The horizontal and vertical leaf distributions (Table 1) assume fixed leaf and azimuth angles. The spherical and ellipsoidal arrangement assumes both random inclination and azimuth angles in a canopy [19].

Table 1. Extinction coefficient, k, as function of solar altitude, β, for various leaf angle distributions. (a: where x is the ratio of the horizontal to the vertical axis of the elliptical and A≈ (x + 1.774 (x + 1.182) - 0.733)/x, [19]).

LEAF ANGLE DISTRIBUTION	**LEAF ARRANGEMENT ASSUMPTION**	**EXTINCTION COEFFICIENT (*K*)**
HORIZONTAL	Fix horizontal leaf	$k = 1$
VERTICAL	Fix vertical leaf	$k = (2 \operatorname{Cot} \beta)/\pi$
SPHERICAL	Variable leaf angle, and variable azimuth angle	$k = 1/(2 \operatorname{Sin} \beta)$
ELLIPSOIDAL^{A}	Variable leaf angle, and variable azimuth angle	$k = (x^2 + \operatorname{Cot}^2 \beta)^{1/2}/(Ax)$

Based on a spherical projected leaf area (Figure 1), Lumeur and Blad [25] and Isobe [26] provide tables with extinction coefficient values for canopies with random azimuth and specific leaf inclination angles for various solar altitudes. Table 2 shows the theoretical *k* values reported by Lumeur and Blad [25].

Table 2. Extinction coefficients, k, for various leaf inclinations, α, and solar altitudes, β

α **β**	**0°**	**15°**	**30°**	**45°**	**60°**	**75°**	**90°**
15°	1.000	0.966	1.1313	1.740	2.082	2.300	2.376
30°	1.000	0.966	0.866	0.914	1.008	1.078	1.103
45°	1.000	0.966	0.866	0.707	0.646	0.637	0.637
60°	1.000	0.966	0.866	0.707	0.500	0.394	0.367
75°	1.000	0.966	0.866	0.707	0.500	0.259	0.170
90°	1.000	0.966	0.866	0.707	0.500	0.259	0.000

According to Lumeur and Blad, Table 2 provides more accurate estimates of *k* values than does the simple spherical model (Table 1). That is because their detailed approach accounts for specific leaf inclination angles, whereas the simple spherical model does not.

To examine the differences in the level of precision of *k* between the simplified spherical model and the detailed approach utilized by Lumeur and Blad, a comparative study was conducted. The literature review below identifies the suitable extinction coefficient values corresponding with the leaf tilt angles of vines.

Many plant species respond to solar radiation by adjusting their leaf angles. Darwin [27] observed two rapid and reversible leaf movement for vines: diaheliotropic, where a leaf's movements track the sun such that the leaf is perpendicular to the sun's rays so as to maximize solar exposure, and paraheliotropic, where a leaf's movement tracks the sun so that the leaf is parallel to the sun's rays so as to minimize solar exposure.

Forseth and Teramura reported two different behaviors for the exposed and shaded leaves of *Puernaria lobate*, or Kudzu vine, in central Maryland, United States. The exposed leaves had random azimuth orientations while maintaining a diurnal orientation away from the sun. In July, when the canopy was mature, they observed a maximum mean angle of 75° (midday) and a minimum mean angle of 30° (sunset) from the horizontal.

R. Smart [28] reported mean leaf angles of 45°, 60° to 75°, and 75° for Concord, Cabernet Sauvignon, and Gewurztraminer, respectively. Similar to Forseth and Teramura [29], he observed that the angles of grapevine leaves change depending on solar radiation conditions. To find the best canopy density for maximum solar exposure, he used the average values of leaf orientations in a canopy. This method is effective because the average values provide reliable results with relatively small errors—specifically, 11% error for the canopy productivity term [30].

H. Mabrouk et al. [31] studied the light distribution in three different training systems for fifteen-year-old Merlot vines in France. They measured the inclination and azimuth angles of leaves in mid-July. The times of the measurements were not included in the study. They reported leaf inclination angles of 57.78° for a low vigor canopy and 53.30° and 54.34° for moderate vigor canopies. They also observed that the leaves exhibited random azimuth angle distributions for the Open Lyre training system. For the Open Lyre training system and the Geneva Double Curtain training system, the leaves were mostly oriented perpendicular to the row direction.

Iandolino et al. [32] measured the leaf inclination and azimuth angles of an eighteen-year-old Cabernet Sauvignon in a vineyard located near Oakville, California. The measurements were conducted in mid-August. The times of the measurements were not reported. They reported leaf inclination angles of 58.1° for an irrigated and non-fertilized vine, and 63.2° for an irrigated and fertilized vine. They also observed random azimuth angle distributions for both of the irrigated vines.

O. Grant et al. [33] measured both inclination and azimuth angles of leaves for two grapevines (Castelao and Aragones) in south-east Chile during August. All the vines were trained on bilateral Royal Cordon systems. The measurements were taken during the morning and afternoon for four different vine treatments: (a) not irrigated (rain-fed), (b) partial root zone drying (only half of the root was irrigated), (c) deficit irrigated (half irrigation provided), and (d) fully irrigated. They report leaf inclination angles of 40° to 80° and an azimuth angle of 180° where leaves were oriented perpendicular to the row direction.

O. Grant et al. [33] reported the widest range of leaf inclination angles because they did not separate the inclination angles according to irrigation regimes. This differentiation is important because leaves under water stress have smaller leaf elevation angles [32].

Table 3. Leaf inclination angles for various vines

Vine type	***Mean leaf angle from horizontal***	***Azimuth angle***	***Reference***
Kudzu	30° to 75°	Random	I. Forest and A. Teramura (1986)
Concord	45°	-	R. Smart (1985)
Cabernet Sauvignon	60° to 75°	-	R. Smart (1985)
Gewurztraminer	75°	-	R. Smart (1985)
Merlot	54.34°	Random	H. Mabrouk et al. (1997)
Merlot	53.30°	Perpendicular to row	H. Mabrouk et al. (1997)
Merlot	57.78°	Perpendicular to row	H. Mabrouk et al. (1997)
Cabernet Sauvignon	58.1°	Random	A. Iandolino et al. (2013)
Cabernet Sauvignon	63.2°	Random	A. Iandolino et al. (2013)
Castelao and Aragones	40° to 80°	Perpendicular to row	O. Grant et al. (2006)

Table 3 summarizes the reviewed leaf inclination and azimuth angles for various vine types. It shows that the range of inclination angles varies between 30° and 80° from the horizon. It is important to note that the lowest angle of 30° belongs to the rain-fed Kudzu vine. For this study, we have assumed that both nutrients and water are limitless. Therefore, from Table 2, the extinction coefficients corresponding with leaf inclination angles from 45° to 80° were considered for the comparative study.

Furthermore, four out of seven studies observed random azimuth angles. This assumption is consistent with the findings of other researchers who have investigated theories of light distribution within canopies [26]. Accordingly, the spherical model, Equation (1), was selected.

$$\mathbf{k} = \frac{\mathbf{1}}{\mathbf{2}\ \boldsymbol{sin}\ \boldsymbol{\beta}} \tag{1}$$

Figure 2 shows k as a function of β (solar altitudes in degrees). The graph illustrates that as the sun reaches an altitude of 90°, the solar radiation penetration through the canopy increases while k decreases.

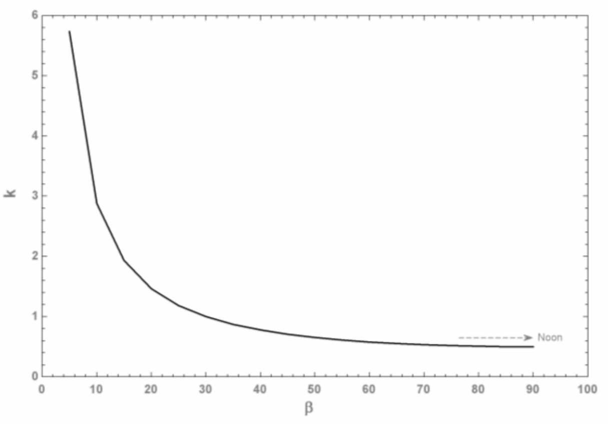


Figure 2. Extinction coefficient, k, as a function of solar elevation, β

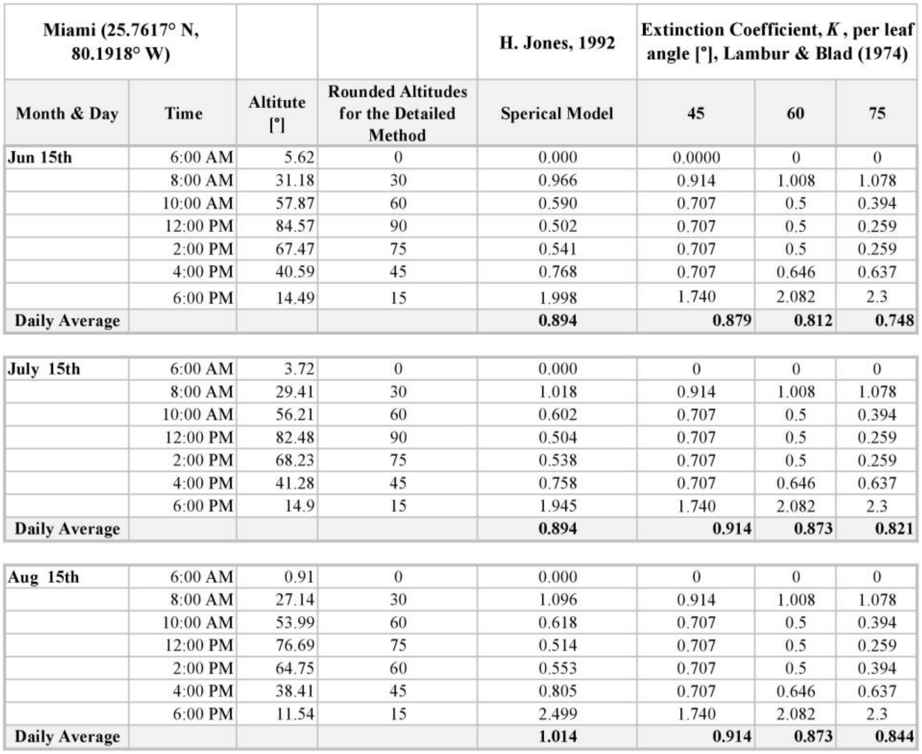
Two cities (New York City and Miami) in different latitudes were selected. The average daily extinction coefficients for the 15th of each summer month were calculated using both the detailed Lumeur and Blad [25] approach and the general Equation (1) approach. The results were then compared to determine the best method.

Although *k* varies with solar altitude and the relative contributions of leaves, Jackson and Palmer [34] discovered the average *k* over time is relevant to the estimation of daily or weekly interception. Accordingly, the daily average extinction coefficient was calculated by averaging the *k* values obtained every two hours from 6 a.m. to 6 p.m. This twelve-hour time period roughly tracks sunrise to sunset for each location.

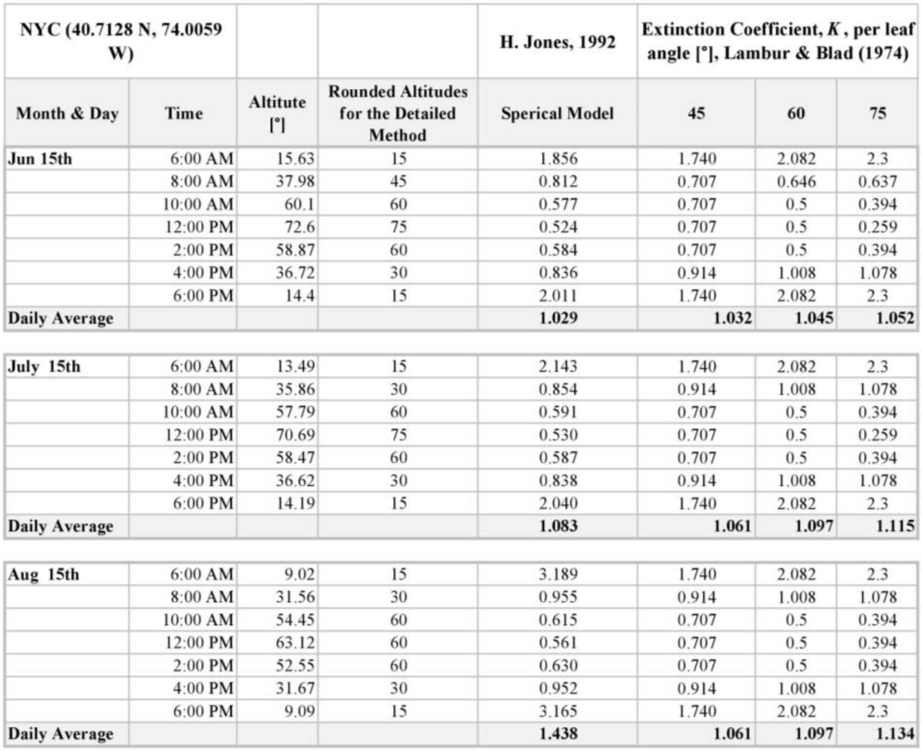
The solar altitudes for each city and time were obtained using the National Oceanic and Atmospheric Administration (NOAA) Solar Position Calculator [35]. The daily average values were calculated from the sunlit hours of the day. In other words, if the solar altitude was 0°, the corresponding time period was not considered for the calculation of the average daily *k* value.

Table 4 shows the results of the comparative studies of New York City and Miami. The rounded solar altitude, *β*, was used for the detailed calculations whereas the exact altitude values were used for the general method. Three different solar inclination angles, *α*, were considered for the detailed method. The general model assumes vertical leaves. Both methods assume random azimuth angles for the leaves.

Table 4. Comparative study of extinction coefficient, k. values using the detailed, Lumeur and Blad [25], and general, Equation (1), methods for Miami and New York City from 6 a.m. to 6 p.m. of the 15th of each summer month.



Miami (25.7617° N, 80.1918° W)				H. Jones, 1992	Extinction Coefficient, K, per leaf angle [°], Lambur & Blad (1974)		
Month & Day	**Time**	**Altitute [°]**	**Rounded Altitudes for the Detailed Method**	**Sperical Model**	**45**	**60**	**75**
Jun 15th	6:00 AM	5.62	0	0.000	0.0000	0	0
	8:00 AM	31.18	30	0.966	0.914	1.008	1.078
	10:00 AM	57.87	60	0.590	0.707	0.5	0.394
	12:00 PM	84.57	90	0.502	0.707	0.5	0.259
	2:00 PM	67.47	75	0.541	0.707	0.5	0.259
	4:00 PM	40.59	45	0.768	0.707	0.646	0.637
	6:00 PM	14.49	15	1.998	1.740	2.082	2.3
Daily Average				**0.894**	**0.879**	**0.812**	**0.748**
July 15th	6:00 AM	3.72	0	0.000	0	0	0
	8:00 AM	29.41	30	1.018	0.914	1.008	1.078
	10:00 AM	56.21	60	0.602	0.707	0.5	0.394
	12:00 PM	82.48	90	0.504	0.707	0.5	0.259
	2:00 PM	68.23	75	0.538	0.707	0.5	0.259
	4:00 PM	41.28	45	0.758	0.707	0.646	0.637
	6:00 PM	14.9	15	1.945	1.740	2.082	2.3
Daily Average				**0.894**	**0.914**	**0.873**	**0.821**
Aug 15th	6:00 AM	0.91	0	0.000	0	0	0
	8:00 AM	27.14	30	1.096	0.914	1.008	1.078
	10:00 AM	53.99	60	0.618	0.707	0.5	0.394
	12:00 PM	76.69	75	0.514	0.707	0.5	0.259
	2:00 PM	64.75	60	0.553	0.707	0.5	0.394
	4:00 PM	38.41	45	0.805	0.707	0.646	0.637
	6:00 PM	11.54	15	2.499	1.740	2.082	2.3
Daily Average				**1.014**	**0.914**	**0.873**	**0.844**



NYC (40.7128 N, 74.0059 W)				H. Jones, 1992	Extinction Coefficient, K, per leaf angle [°], Lambur & Blad (1974)		
Month & Day	**Time**	**Altitute [°]**	**Rounded Altitudes for the Detailed Method**	**Sperical Model**	**45**	**60**	**75**
Jun 15th	6:00 AM	15.63	15	1.856	1.740	2.082	2.3
	8:00 AM	37.98	45	0.812	0.707	0.646	0.637
	10:00 AM	60.1	60	0.577	0.707	0.5	0.394
	12:00 PM	72.6	75	0.524	0.707	0.5	0.259
	2:00 PM	58.87	60	0.584	0.707	0.5	0.394
	4:00 PM	36.72	30	0.836	0.914	1.008	1.078
	6:00 PM	14.4	15	2.011	1.740	2.082	2.3
Daily Average				**1.029**	**1.032**	**1.045**	**1.052**
July 15th	6:00 AM	13.49	15	2.143	1.740	2.082	2.3
	8:00 AM	35.86	30	0.854	0.914	1.008	1.078
	10:00 AM	57.79	60	0.591	0.707	0.5	0.394
	12:00 PM	70.69	75	0.530	0.707	0.5	0.259
	2:00 PM	58.47	60	0.587	0.707	0.5	0.394
	4:00 PM	36.62	30	0.838	0.914	1.008	1.078
	6:00 PM	14.19	15	2.040	1.740	2.082	2.3
Daily Average				**1.083**	**1.061**	**1.097**	**1.115**
Aug 15th	6:00 AM	9.02	15	3.189	1.740	2.082	2.3
	8:00 AM	31.56	30	0.955	0.914	1.008	1.078
	10:00 AM	54.45	60	0.615	0.707	0.5	0.394
	12:00 PM	63.12	60	0.561	0.707	0.5	0.394
	2:00 PM	52.55	60	0.630	0.707	0.5	0.394
	4:00 PM	31.67	30	0.952	0.914	1.008	1.078
	6:00 PM	9.09	15	3.165	1.740	2.082	2.3
Daily Average				**1.438**	**1.061**	**1.097**	**1.134**

Except in the month of August, the differences between the *k* values using Lumeur and Blad's detailed method (Table 2) and the simplified model, Equation (1), were negligible. For the month of August, for Miami and New York, the maximum percentage differences for the predicted extinction coefficients are 15% and 30%, respectively. As will be discussed later, at such large values of *k*, its significance on canopy transmittance is minimal.

This comparative study shows that, for various latitudes, the simplified model, Equation (1), provides a good estimate of extinction coefficient values compared to the detailed approach introduced by Lumeur and Blad [25]. Also, the results demonstrate a few interesting trends:

- The value of *k* decreases as the latitude of the site decreases. Recall that the model assumes vertical leaves with random azimuth distributions. The solar radiation from the relatively low solar noon altitude angle in cool climates is mostly blocked from entering the canopy. In hot climates, where the solar noon elevations are high, light can easily penetrate the canopy.
- For both sites, the *k* value for the month of August is the largest. This is due to the reduction in solar altitude compared to the months of June and July. Similarly, because the leaves are vertical, solar radiation is mostly blocked by the leaves, reducing the canopy transmittance.
- Field studies show that *k* values of 1.0 are associated with horizontal leaves [19]. Therefore, it seems that the statistical model overestimates the capacity of the canopy to block sunlight.

Empirical Method Defining Extinction Coefficient (*k*)

In practice, these simple geometric approximations cannot easily be translated to describe real canopy behavior [19,20]. Empirically derived values for the extinction coefficient vary between 0.3 and 1.5, depending on the species of vine considered. Assuming water- and nutrient-limitless conditions, values less than 1.0 are observed for non-horizontal and irregularly distributed leaves. Values equal to or greater than 1.0 occur with horizontal or more evenly distributed leaves [19].

The field measured values of *k* for trained grapevine canopies can serve as a good estimate for green walls because the geometries of the two canopies are similar. There are four major variations of grapevine trellis training systems [36]:

1. Head/spur, which basically consists of a short trunk with several two-node bearing units (e.g., bush vine)
2. Head/cane, which consists of a short trunk with one or more longer bearing units (e.g., Guyot)
3. Cordon/spur, which involves horizontal training of the arm(s) with several two-node spurs (e.g., midwire cordon)
4. Cordon/cane, which is similar to head/spur but with longer bearing units (e.g., Sylvoz)

Except for the head/spur training system, all the systems can produce canopy geometries similar to those of a vining green wall. Therefore, the major defining design factors to consider are the methods of management (i.e., the position of the shoots) and the division of the canopies.

There are two major types of shoot arrangements: (a) vertical shoot positioning (VSP), where the shoots are positioned upright to increase solar exposure, and (b) non-VSP, where the shoots are allowed to grow and cascade in their natural directions (e.g., top wire cordon) [36]. It is imperative that green wall geometries are most similar to VSP arrangements.

Canopy division is implemented so that two or more canopies are created from the initial single canopy curtain through the configuration of the trellis [36]. A canopy can be divided horizontally or vertically. In either case, the goal is to improve the solar exposure of the canopy and, by extension, its growth rate. Horizontally divided training systems are not similar to green walls and therefore are excluded from this investigation.

Undivided and vertically divided canopies with VSP shoot positioning (both upward and downward shoot positioning) can closely mimic green wall geometries. Therefore, the field measured extinction coefficient values from such training systems can be used as a good estimate of the *k* values for green walls.

M. Bindi et. al. [37] introduced a model for simulating the growth and development of grapevines in Conegliano, Italy (Latitude of 43.75° N). The model was verified through a field study on Sangiovese cultivars that were cordon trained (vertical trellises). They found a *k* value of 0.5.

B. Wermelinger and J. Baumgartner [38] developed and tested a mathematical model to account for the carbon assimilation of grapevines located at Northern Switzerland (latitude of 47° N). Although the study did not specify the training system used, it states that the vines were double cane pruned. This pruning method is analogous to the double Guyot system, which most likely requires a VSP canopy arrangement [38]. The model was successful in predicting carbon assimilation values using a seasonal *k* value of 0.6.

P.Cavallo et al. [39] measured the daily extinction coefficients of different types of grapevine training systems in Basilicata, southern Italy (latitude of 40.60° N). They observed *k* values of 0.63 for the Bilateral Guyot system and 0.62 for the Bilateral Spur-Pruned Cordon system in August.

The field measured *k* values of the trained grapevines show good agreement with some of the reported k values for green walls. Note that with the exception of L. Schumann [5], Equation (2) was used to calculate the *k* values from the reported solar radiation transmitted through the green wall, called “canopy transmittance”. Canopy transmittance is a function of both *k* and the leaf area index (LAI)--which, in the context of green walls, is a dimensionless value describing the ratio of leaf area to a unit wall area [19,40]. For summer months, LAIs of 3, 4, and 5 are common for green walls [5,24].

$$\mathbf{I}/\mathbf{I_0} = \mathbf{e}^{-\mathbf{K\,LAI}} \tag{2}$$

Where
I Irradiance passing through a canopy [W/m^2]
I_o Irradiance above of the canopy [W/m^2]
k Extinction coefficient [-]
LAI Leaf area index [-]

L. Schumann [5] measured the transmittances of green walls against a southeast-facing barn in Southern Maryland, United States (latitude of 39° N). She observed *k* values between 0.5 and 0.6 for LAIs of 3, 4 and, 5.

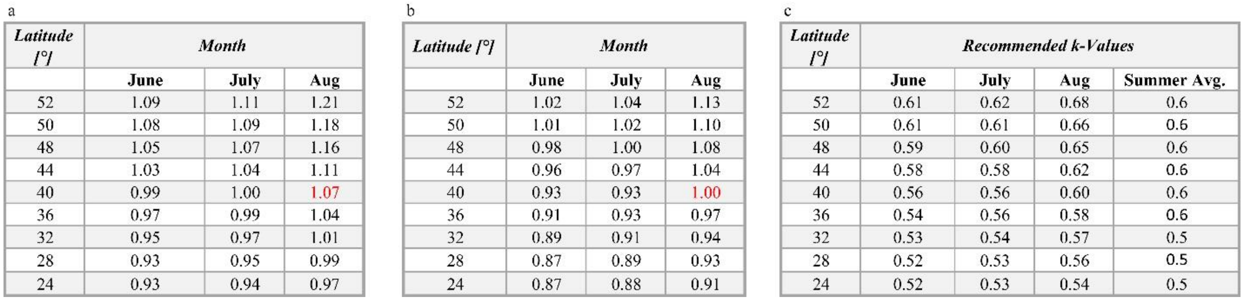
Perez et al. [11] conducted a thorough investigation to establish a relationship between the LAI and transmittance of an indirect vining (Boston ivy) green wall in Lleida, Spain (latitude of 42° N). The green wall was affixed around a building, covering the south-, east-, and west-facing façades to various extents. They observed average LAI values of 3.5, 3, and 2.4 for the east-, south-, and west-facing orientations, respectively. The low LAI values on the south- and west-facing façades were attributed to a shorter growth period compared to the east façade. They observed an average solar transmittance of 6% to 8% for the lower and middle sections of the south- and west-facing green walls. According to their findings, the associated *k* value was approximately 0.6 on August 15th.

Recommended *k* Values- Comparative analysis of empirical and statistical methods

It was demonstrated above that extinction coefficient values differ according to the latitude of a site and the month of observation. Table 5(a) shows the average *k* for various latitudes for each summer month based on the spherical model, Equation (1).

To obtain the monthly average values of *k*, the elevations of the sun at the solar noon of the 15th of each summer month were calculated using the National Oceanic and Atmospheric Administration (NOAA) Solar Position Calculator [35]. Because in most site conditions the solar radiation at sunrise and sunset is blocked from reaching the façade of a building due to various obstacles such as surrounding buildings, the minimum solar altitudes were considered to be 10° for morning and evening conditions. In other words, the monthly average *k* values for the listed latitudes were obtained by averaging the *k* values for each solar altitude angle, starting from 10° at sunrise, rising to the altitude at solar noon, and then falling back to 10° at sunset.

Table 5. a) Calculated average daily extinction coefficients from the 15th of each summer month. b) Calculated ratios between k values according to the baseline; i.e., the month of August at a latitude of 40°. c) The adjusted extinction coefficient values for the summer months of various latitudes according to the baseline of the month of August at a latitude of 40°.



a

Latitude [°]	Month		
	June	July	Aug
52	1.09	1.11	1.21
50	1.08	1.09	1.18
48	1.05	1.07	1.16
44	1.03	1.04	1.11
40	0.99	1.00	1.07
36	0.97	0.99	1.04
32	0.95	0.97	1.01
28	0.93	0.95	0.99
24	0.93	0.94	0.97

b

Latitude [°]	Month		
	June	July	Aug
52	1.02	1.04	1.13
50	1.01	1.02	1.10
48	0.98	1.00	1.08
44	0.96	0.97	1.04
40	0.93	0.93	1.00
36	0.91	0.93	0.97
32	0.89	0.91	0.94
28	0.87	0.89	0.93
24	0.87	0.88	0.91

c

Latitude [°]	Recommended k-Values			
	June	July	Aug	Summer Avg.
52	0.61	0.62	0.68	0.6
50	0.61	0.61	0.66	0.6
48	0.59	0.60	0.65	0.6
44	0.58	0.58	0.62	0.6
40	0.56	0.56	0.60	0.6
36	0.54	0.56	0.58	0.6
32	0.53	0.54	0.57	0.5
28	0.52	0.53	0.56	0.5
24	0.52	0.53	0.54	0.5

Although the statistical method proved to overestimate the specific values of the extinction coefficient, the relationships between the coefficients remain valid. This is because the ratios between the values of the extinction coefficients are established according to solar altitude, and not canopy design specifications (Equation (1)).

Since there is general agreement between the reported *k* values of empirical studies of both trained grapevines and green walls for the latitude of 40°, the extinction coefficient for the month of August (1.07) was used as a baseline to establish the ratio of *k* between various latitudes and summer months. Table 5(b) shows the ratios obtained through the division of each *k* value by the baseline ratio of 1.07 (August, Latitude of 40°)

According to the empirical studies, a *k* of 0.6 is most associated with mature canopies at a latitude of 40°. Using this value, the rest of the extinction coefficients were calculated based on the ratios obtained in Table 5(b). Table 5(c) shows the recommended average monthly and seasonal *k* values for various latitudes.

The calculated values of Table 5(c) show good agreement with the reported field measured values of the reviewed literature in different latitudes. For example, for the latitude of 48° N, the average seasonal *k* value is 0.6. This value shows good agreement with the reported *k* values of trained grapevines in Northern Switzerland (latitude of 47° N) [38].

Furthermore, Table 5(c) shows that in latitudes less than or equal to 32°, the average seasonal extinction coefficient is reduced to 0.5 due to high solar altitudes during the summer.

Canopy Transmittance for Recommended *k* Values

Figure 3 shows the canopy transmittance as function of *k* for LAIs of 3, 4, and 5 for both the theoretical method and the recommended *k* values. The *k* values derived from the theoretical model correspond with values larger than 0.9, which values are associated with horizontal leaf tilt angles [19]. For these large *k* values, the canopy transmittance is minimal, especially for values greater than 1.0.

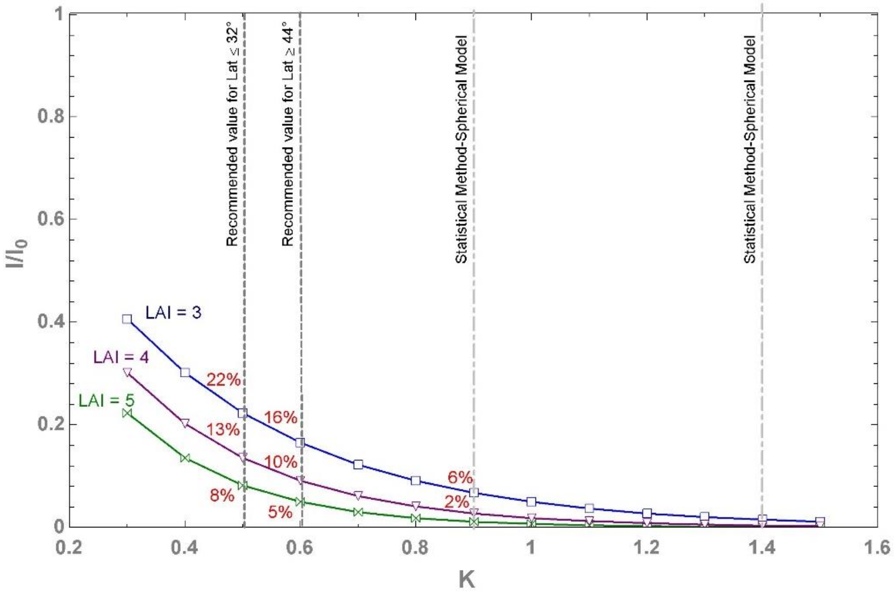


Figure 3. Fraction of light transmittance through a canopy as a function of the extinction coefficient, k, for various Leaf Area Indices (LAI values). The dotted lines are k values obtained from empirical and statistical methods.

By contrast, the recommended *k* values show good agreement with the expected *k* values of canopies with non-horizontal leaf tilt angles, ranging between 0.5 and 0.6 [19]. These values also show good agreement with the reported field measured studies of trained grapevines and vining green walls in similar latitudes [5,11,34,37-39].

The recommended *k* values account for the summer month solar elevations at various latitudes. Accordingly, for latitudes less than or equal to 32°, an extinction coefficient of 0.5 is recommended. For latitudes greater than or equal to 44°, an extinction value of 0.6 is recommended. The *k* values for latitudes between 32° and 44° should be between 0.5 and 0.6 (Table 5(c)).

Furthermore, Figure 3 can be used as a general guideline for the early design phase of a project. It can be used to quickly estimate the fraction of sunlight passing through a canopy for various LAIs. LAIs of 3, 4, and 5 are mostly associated with the months of Jun, July, and August, respectively [5,41-43]. The percent values in red in Figure 3 show the percentage of transmitted solar radiation for different LAIs and extinction coefficients.

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