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Building and Environment
Dr. Qingyan Chen

Lleida, September 27th, 2018

Dear Dr. Qingyan Chen

Here I enclose the **reviewed** manuscript of the paper “Evapotranspiration process in green roofs: a review” authored by Stefano Cascone, Julià Coma, Antonio Gagliano, Gabriel Pérez for your consideration to publish it in Building and Environment. Paper is containing original research and has not been submitted/published earlier in any journal and is not being considered for publication elsewhere. All authors have seen and approved the manuscript and have contributed significantly for the paper.

Ethical Procedure:

- The research meets all applicable standards with regard to the ethics of experimentation and research integrity, and the following is being certified/declared true.
- As an expert scientist and along with co-authors of concerned field, the paper has been submitted with full responsibility, following due ethical procedure, and there is no duplicate publication, fraud, plagiarism, or concerns about animal or human experimentation.

A disclosure/conflict of interest statement:

- None of the authors of this paper has a financial or personal relationship with other people or organizations that could inappropriately influence or bias the content of the paper.
- It is to specifically state that “No Competing interests are at stake and there is No Conflict of Interest” with other people or organizations that could inappropriately influence or bias the content of the paper.

Yours faithfully,

Dr. Gabriel Pérez

Dear Editor and Reviewers, thanks for your suggestions.

Editor's notes

Comment: You need to cite more papers published recently

Thank you for your suggestion. The following papers published recently were cited in the manuscript.

References

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Reviewer #1:

Comment: First, the review is by no means "comprehensive" given the voluminous literature on the very topic. A quick search of "green roof(s)" in titles easily found 800+ papers and vast majority of them were on the evapotranspirative cooling effect. Even to my limited knowledge, there are many important research and publication in recent years from numerous research groups around the world on the topic of investigation being completely ignored in this review; an exhaustive list will be pages long and I leave this for the excise for the authors. Thus the authors either need to expand their literature search to make the review "comprehensive" (which to my opinion is extremely difficult, if not sheerly impossible), or they have to clearly state the criterion on their standard of selection of the literature (e.g. range of years, more specific topics such as on building energy implications, etc.).

The authors thank this reviewer for his/her positive feedback, and really appreciate his/her suggestion to improve the quality of the manuscript. All the comments from this reviewer were addressed below or directly in the body of the paper in red.

The authors agree with the reviewer on the difficulty of conducting a "comprehensive" review on green roofs. Therefore, the abstract was modified following the reviewer's suggestions and the word "comprehensive" has been eliminated. Despite this, several references were considered and added to the article (see reply to editor's comment) to mention some of the numerous recent research on the topic. Furthermore, the text was revised to define the criterion on our standard of selection of the literature, as recommended by the reviewer

Now in the text, lines: 61-66

However, due to the high number of studies carried out on green roofs, this review is focused on the research that expressly evaluate experimentally or analytically the evapotranspiration process in green roofs. Therefore, all researches examining performance and benefits of green roofs without directly correlating them with evapotranspiration is out of the scope of this study. In addition, the previous studies that have evaluated the role of evapotranspiration in the hydraulic performance

and water balance of green roofs, in terms of storm water management and runoff of these systems, are not included in this review.

Comment: Secondly, we found some careless mistake (see specific comments below) in referencing to the previous work that was repeated a couple of times in the manuscript. While this could be as small as a typo, what it reflected cast some skepticism in the overall quality of the study. On the presentation, the structure of the paper need to be improved though the manuscript is overall well written and not difficult to follow.

The authors thank this reviewer for carefully reading the paper and noticing this typo. The quality of the manuscript is increased and careless mistake in referencing to the previous work was avoided following reviewer's suggestions.

Specific Comments:

Comment: 1. Section 2 (line 146), references are needed for energy budget method.

The following references were considered and added to the text.

References

[44] C.Y. Jim, S.W. Tsang, Biophysical properties and thermal performance of an intensive green roof, *Build. Environ.* 46 (2011) 1263–1274. doi:10.1016/j.buildenv.2010.12.013.

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Comment: 2. Table 3, the term 'direct' and 'indirect' used in the types of measurement needs to be defined or explained explicitly.

Thanks for the observation. The manuscript was revised as follows:

Now in the text lines: 507-511

On one hand, the “indirect” measurements presented within this table refer to ET estimation using data derived from the substrate water content. In this case, the water content variation is assumed equal to the ET. On the other hand, “direct” measurements refer to ET estimation using data collected by a lysimeter or load cells, monitoring the evolution of sample weight and not the water content variation in the substrate.

Comment: 3. Some consecutive paragraphs in Section 3.1 contain only one to two sentences, which can be combined together to improve readability.

The text was revised and rewritten in some paragraphs. Changes in red.

Comment: 4. Section 3.2 (line 246), 'tray factor' needs to be defined or referred to related publications.

As recommended by this reviewer, the authors related the “tray factor” with the study carried out by Ouldboukhitine et al. (2012).

Reference [55] S.E. Ouldboukhitine, R. Belarbi, R. Djedjig, Characterization of green roof components: Measurements of thermal and hydrological properties, *Build. Environ.* 56 (2012) 78–85. doi:10.1016/j.buildenv.2012.02.024 was added to the text. The “tray factor” is defined in this paper.

Comment: 5. Some data in Jim and Peng (2012) is used in Table 5 of the manuscript. However, there is possibly a calculation error or type in Table 4 of the original paper (Reference [33]). In Table 4 footnote g, the daily ET is calculated by irrigation minus substrate storage change. For SD (sunny-dry) condition, the irrigation is 0, while the substrate storage change is -8.1, therefore, the daily ET should be 8.1 instead of 13.1. This is either a calculation error of daily ET, or a typo in irrigation value. Since this result and this paper are discussed in the manuscript for several times (line 257, line 293, and line 484-488) and this result is contradicted to the other findings, further checks are necessary.

Thank you for the accurate review. We carefully checked reference [49] (C.Y. Jim, L.L.H. Peng, Substrate moisture effect on water balance and thermal regime of a tropical extensive green roof, *Ecol. Eng.* 47 (2012) 9–23. doi:10.1016/j.ecoleng.2012.06.020) to understand if in table 4 [49] there is “a calculation error of daily ET or a typo in irrigation value”, as suggested by the reviewer.

The following relevant statements are in [49]:

- “... IG is the daily regular irrigation (5 mm) ...” on page 4.
- “... the daily regular irrigation on sunny and cloudy days (analogous to a 5 mm rainfall from 11.00 h to 11.15 h) ...” on page 6.
- “... The daily 5-mm irrigation on sunny and cloudy days ...” on page 13.
- We concluded that in sunny day the irrigation was 5 mm and not 0. Therefore, the irrigation value was 13.1 mm, as reported in table 4 [49].

The text was revised according to the data reported in [49], see changes in red (Lines 183-191, 605-611 and 641-645).

Comment: 6. In Table 5 Reference [33], the minimum value uses the data of substrate storage change in the original paper, while the maximum value uses the daily ET data. They are possibly not equivalent.

The authors agree with the reviewer suggestion, the data reported is not equivalent. The minimum values from ref [49] have been removed from Table 5.

Comment: 7. Section 3,4, and 5, discuss ET estimations from direct measurements, mathematical modeling, and dynamic simulation, while Section 6 and 7 discuss the parameters (meteorological and plant-substrate) that influence ET and summarize ET studies in different climates (Table 9-11). It could be better if put Section 6 and 7 before Section 3,4, and 5 to create a better logic sequence. Otherwise, the latter part of Section 5, where climate, seasonality, LAI, etc. are discussed, seems not fit the topic of the section.

The manuscript was structured as suggested by the reviewer #1. Furthermore, a sub-section named ET results using EnergyPlus was created to separate the latter part of Section 7 (ex Section 5) from the other part of the section. The organization of revised paper is the following:

Now in the text, lines: 69-75

Section 3 and 4 show the main climatological parameters and characteristics of vegetation and substrate that influence the ET of green roofs, respectively. Section 5 describes the principal experimental measurement methods used to evaluate the evapotranspiration of green roofs, the results obtained from them and a summary of the different units of measurement used. Section 6 describes the mathematical models that take into account the latent heat within a green roof energy balance and their main outcomes. In section 7, the main findings derived from research performed using dynamic simulation software are reported.

Comment: 8. Table 9-11 could be combined as they have the same title. Table 8 could also be combined to Table 9-11 to form a large informative table to improve readability and reduce replicate content.

The authors agree with the reviewer's comment. Table 9, 10 and 11 were combined in Table 4 providing a large informative table. See the new table 4 in red (pag. 13).

Comment: 9. Section 6 (line 543-546, line 564-565), further explanations in detail of the controversial results are necessary.

The authors provided further explanations regarding the controversial results in section 6. The text was revised as follows:

Now in the text, lines: 270-277

In a Cwa climatic area where the relative humidity and the air temperature varied between 50%, 23 °C in autumn, and 80%, 36 °C in summer, Jim and Tsang (2011) [47] found that the highest transpiration rate is observed in autumn rather than in summer, because of low relative humidity and mild air temperature. According to this study, evapotranspiration is minimized in a humid environment and the high relative humidity is the crucial factor that dampens the transpiration rate. Unlike the green roof in the temperate region, the experiment carried out by Jim and Tsang [47] showed that the transpiration rate of an intensive green roof in the humid-subtropical region, dominated by the Monsoon climate system, depends mainly on photosynthetically active radiation and relative humidity.

Now in the text, lines: 251-257

Jim and Tsang (2011) [47] found a rather modest correlation between the wind above the canopy and transpiration, so the wind should not play a major role in facilitating the transpiration rate. Figure 2 shows the sunny and rainy wind speed measured at canopy top in [47]. The wind speed was relatively higher on rainy days than on sunny ones. The wind speed on rainy and sunny days averaged at 3 ms^{-1} and 1 ms^{-1} respectively. The correlation coefficients between wind and transpiration at -0.1 to 0.1 ($p \leq 0.05$) was weak. Although wind speed was higher on rainy days, the associated high relative humidity suppresses transpiration.

Comment: 10. Figure 3, the meaning of 'based on 150 mm water holding capacity' is not clear. Further explanation of this figure is needed, and a better citation is required.

Thanks for the comment. The manuscript was revised and the meaning of water holding capacity was clarified. Furthermore, a better citation was provided.

Now in the text, lines: 308-312

The Water Holding Capacity is the total amount of water available for plants that is held against gravity in a soil and is usually estimated as the amount present at -0.03 MPa average water

potential minus the amount present at -1.5 MPa water potential. In [71], the authors stated that it is a very important soil characteristic strongly and positively correlated to the inherent productivity of soils.

Reference:

[71] C.E. Seubert, C.S.T. Daughtry, D.A. Holt, M.F. Baumgardner, Aggregating Available Soil Water Holding Capacity Data for Crop Yield Models, 1984.

Comment: 11. Section 7.3, stomatal conductance and resistance, and their relation need to be defined separately.

Two sub-sections named 4.3. Stomatal resistance and 4.4 Stomatal conductance were created following reviewer's suggestions.

Comment: 12. Section 8 (line 792), the second order polynomial regression is not appropriate for all parameters, especially when the data points are scarce (only 4 data points). Though the regression curves have r-square close to 1, it doesn't explain the true relations between the parameters and ET. For certain parameters, such as wind speed, relative humidity, VWC, LAI, and stomatal resistance, linear regression is better to illustrate the monotonicity of their relation to ET.

The authors agree with the use of a linear regression to illustrate the monotonicity of the relation of relative humidity, VWC, stomatal resistance, and external factor. Thus, the new equation of regressions are proposed.

Otherwise, as regard wind speed and LAI, using more than four data points are available, the use of linear regressions does not provide accurate results. Probably there is not a strictly monotonicity among of wind speed, LAI and the ET. Thus for LAI and wind speed the authors prefer to use a second order polynomial regression.

Comment: 13. Section 9, the manuscript states the main purpose of this study is to review the impact of ET on the energy performance of green roofs. However, line 834-836 states 'there is no studies correlating ET with external surface temperature' and the main content in Section 2-8 is focused on ET estimation over green roofs or load cells. The manuscript shows very few contents related to the energy performance of green roofs, therefore the main purpose of this article is not fulfilled. More contents could be added to serve the proposed purpose of this manuscript such as but not limited to: the topics about 1) the relation between green roofs and external/internal building

temperature; 2) the relation between green roofs and building energy consumption for cooling; 3) the relation between green roofs and human thermal comfort in buildings.

We are sorry, the statement on the energy performance in the conclusion was a refuse. The text of Section 9 was revised according with the main purpose of the study.

Comment: 14. Check typos (e.g. line 450) and abbreviations that not defined (e.g. line 466).

All the manuscript was revised and the typos were avoided.

Reviewer #3:

The authors thank the reviewer for his/her positive feedback. All the comments from this reviewer were addressed below or directly in the body of the paper in red.

Comment: Please avoid the double row number the next time!!!

The authors agree with the reviewer. In the word file there is only one row. The editorial manager automatically create the second row in the final pdf file. The new version will avoid one of the two row numbers.

Comment: Keywords: some keywords are already present in the paper title, I suggest to change them.

Thanks for the suggestion. The authors changed the keywords.

Comment: L 31-32: define better the UHI (Urban heat Island) effect

The authors introduced a better definition of the UHI effect. In addition, some references were added to the paper.

Now in the text, lines: 31-33

Furthermore, these areas often have higher air temperatures than their rural surroundings which is commonly called urban heat island (UHI) effect [3,4].

References:

[3] M.T. Hoelscher, T. Nehls, B. Jänicke, G. Wessolek, Quantifying cooling effects of facade greening: Shading, transpiration and insulation, Energy Build. 114 (2016) 283–290. doi:10.1016/j.enbuild.2015.06.047.

[4] O. Buchin, M.T. Hoelscher, F. Meier, T. Nehls, F. Ziegler, Evaluation of the health-risk reduction potential of countermeasures to urban heat islands, Energy Build. 114 (2016) 27–37. doi:10.1016/j.enbuild.2015.06.038.

Comment: L 45: I am not sure that evapotranspiration plays an "important" role in storm-water management and peak flow mitigation, please explain better

The authors agree with the reviewer's comment. Evapotranspiration is related to the hydrological cycle of green roof, however, it does not play a fundamental role in storm-water management and peak flow mitigation. The text was revised according to reviewer's observations.

Comment: L 68: I suggest "...in green roofs,.." in place of "...of green roof,.."

In agreement with the reviewer's comment the text was changed.

Comment: L 81: why "Transpiration" with T in capital letter?

The authors thank this reviewer for noticing the typo. All the document has been reviewed.

Comment: L 82: ".. on the underside of leaves...", in some cases it occurs also on the upper side of the leaf

The authors agree with the reviewer and the text was changed.

Comment: L 99: define better LAI, it is a very important parameter

The authors thank this reviewer for underlying a crucial point of their work, which was not explained in a sufficiently clear manner.

Now in the text, lines: 102-108

In particular, the characteristic of the vegetation that is most important from the standpoint of impacts on the heat transfer through the roof is the leaf area index (LAI). LAI is established as the one-sided green leaf area per unit ground surface area ($LAI = \text{leaf area}/\text{ground area}$, m^2/m^2) in broadleaf canopies. The LAI value depends on the type and the growth phase of the plant (crop), usually ranging from 0 to 10.. E.g., if the average parcel of roof surface is beneath two leaves, the corresponding LAI is 2. Values of LAI for green roofs vary depending upon plant type, but are typically in the range of 0.5–5.0 [34].

Reference

[34] D.J. Watson, Comparative Physiological Studies on the Growth of Field Crops: I. Variation in Net Assimilation Rate and Leaf Area between Species and Varieties, and within and between Years, Ann. Bot. 11 (1947) 41–76. doi:10.1093/oxfordjournals.aob.a083148.

Comment: L 140: table 2, describe if the models refer to daily, hourly etc values

Thanks for the comment. The text was revised adding the modeling time step.

Comment: L 221: table 4, please write "From" on the first column and "To" on the first row of the table. The unit of the power per unit area of the last column (W/m²/day) doesn't make sense.

I am not sure of the conversion factors:

1 mm/day corresponds to 1 L/m²/day and to 2.45 MJ/m²/day = 2450000 J/m²/ 86400 s = 28.36 W/m², I read 0.035.

I suppose that L/m²/s is wrong.

1 W/m² = 1 J/s/m² that corresponds to 1 J/s/m² x 86400 s = 0.086 MJ/m²/day that corresponds to 0.086 MJ/m²/day / 2.45 MJ/kg = 0.035 kg/m²/day=0.035 mm/day, I read 28.57.

Please verify all the table 4.

The authors thank this reviewer for carefully reading the paper and noticing these errors. Thus, the authors verified all data in the new Table 6 (ex Table 4). The power unit of measurements is now W/m². The conversion factors were revised as suggested by the reviewer, 1 mm/day = 28.36 W/m². The unit L/m²/s was a typo, so it was modified in L/m²/day. Finally, 1 W/m² = 0.035 mm.

Comment: L 312-313: "An increase in the evapotranspiration rate decreases the convection heat flux related to sensible heat and storage." Add reference

The following reference has been added:

[61] S.W. Tsang, C.Y. Jim, Theoretical evaluation of thermal and energy performance of tropical green roofs, Energy. 36 (2011) 3590–3598. doi:10.1016/j.energy.2011.03.072.

Comment: L 334: table 6, add other parameters, for example the input variables of the models

Many thanks for the suggestion. Model input data have been added to the table, increasing the readability and information provided.

Comment: L 427: "Table 7 provides data .." does the data term stand for "input data"? Please correct

The authors agree with the reviewer's comment. It has been corrected in the paper.

Comment: L 432: table 7, is the "Parameter" the "Input Parameter", if yes correct it

Yes, it is "Input Parameter". The word in the table has been changed.

Comment: L 438: "...the average monthly ..." does it refer to the evapotranspiration flux? Please explain

Yes, it refers to evapotranspiration. Boafo et al. (2017) investigated the potential contribution of the average monthly evapotranspiration in green roofs. The text was revised according to reviewer comment.

Comment: L 466 is SR the solar radiation? Please define before and add to the Nomenclature
Yes, it means solar radiation. The text was modified.

Comment: L 511: indicate or indicates?
Thanks to detect the grammar typos.

Comment: L 548: "sun air" ???
Thanks to the reviewer for this accurate review, "sun air" was a mistake. The correct word is "solar radiation". It has been changed in the manuscript.

Comment: L 563: "... that air... " air temperature ?
In the revised paper, this part of the text was deleted.

Comment: L 647: "substrate reflectivity" specify the wavelength range of the reflectivity
Thanks for the comment. The manuscript was revised as follows:

Now in the text, lines: 377-378

Soil reflectivity depends on soil type and water content that typically varies from 0.10 for wet soil to 0.35 for dry soil.

Comment: L 700: "AC" please explain the term and add to the Nomenclature
It means air conditioning. The text was corrected.

Comment: L 716: check the parenthesis
The parenthesis are actually correct.

Comment: L 775: please explain the relationship of the "external coefficient" with the long and short wave radiation
Thanks for the observation. The paper has been modified as follows:

Now in the text, lines: 838-839

Where the radiation emitted from earth/atmosphere is terrestrial or longwave radiation and the radiation emitted from sun is solar or shortwave radiation.

Comment: Nomenclature: Missing terms, see for example "SR" and "AC". Explain if TD refers to a day.

“SR” means solar radiation and “AC” means air conditioning. TD refers to a day. The text was corrected.

The evapotranspiration process in green roofs: a review

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Abstract

Previous research has shown that most of the green roof benefits are related to the cooling effect. In the literature available, however, it is still not clear how and how much the evapotranspiration affects the performance of a green roof. In order to fill the gap in this research topic, this study carries out a review on the cooling effect due to the evapotranspiration process of green roofs. First of all, an overview of the evapotranspiration phenomenon in green roofs, as well as the equipment and methods used for its measurement are presented. Then, the main experimental results available in literature, the physical-mathematical models and the dynamic simulation software used for the evaluation of the latent heat flux are also analysed and discussed among the available literature. Moreover, this review proposes a classification of the results carried out by previous studies as function of the main parameters affecting the evapotranspiration process (e.g. volumetric water content, stomatal resistance, Leaf Area Index, solar radiation, wind velocity, relative humidity, soil thickness, and substrate composition). Additionally, a sensitivity analysis of the results obtained from the literature allowed underlining the correlation among the main factors affecting the evapotranspiration. Finally, a vision of the world area where green roof studies were performed is provided. From the results, it is possible to emphasize that most of the studies that evaluated the evapotranspiration used high precision load cells. Furthermore, all the heat transfer models of green roofs considered in this review took into account the latent heat flux due to evaporation of water from the substrate and plants transpiration, however, only few of them were experimentally validated.

Keywords: evaporation; transpiration; latent heat flux; cooling effect;

29 **1. Introduction**

30 In recent years, the continued growth of high-density urban areas, characterized by extensive paved areas,
31 have increased the overwarming and energy needs within the cities [1,2]. Furthermore, these areas often have
32 higher air temperatures than their rural surroundings which is commonly called urban heat island (UHI)
33 effect [3,4]. Engineers, researchers, and designers are committed to develop sustainable solutions to reduce
34 both energy consumption and pollutant emissions by using innovative materials and technologies [5,6]. One
35 of the most effective solutions adopted in the field of bioclimatic architecture is the replacement of materials
36 traditionally used in flat roofs, which comprise around 25% of the total horizontal surfaces in urban areas,
37 with green roof technologies [7].

38 Green roofs provide several benefits at both building and city level. The following are the most commonly
39 observed at urban scale: mitigation of urban heat island effect [8–10]; decrease in storm water runoff [11,12];
40 enhancement of biodiversity in densely urban areas [13]; purification of air and water runoff [14]. At
41 building scale, green roofs reduce the sensible heat flux due to the cooling effect [15,16] thus decreasing the
42 heating and cooling demand of a building [17–19], and improving human thermal comfort [20,21]. This
43 effect may vary depending on the climate conditions [22–24], and the level of insulation specially in cases of
44 building retrofitting [25,26]. Most of these multiple benefits are linked to the cooling effect due to the
45 evapotranspiration process (ET) that humidifies the external ambient air, reduces the surface temperature of
46 the roof [27], and mitigates the urban heat island phenomenon [28].

47 Previous studies have considered the cooling effect due to the evapotranspiration process among the major
48 energy benefits of green roofs [29,30]. The importance of evapotranspiration in energy transfer models was
49 also highlighted in previous studies [31] in which the authors analysed the vegetation effect on horizontal
50 surfaces in urban, suburban and agricultural environments. However, the existent literature is scarce and
51 controversial in evaluating the physical-mathematical models and dynamic simulation software for
52 calculating ET, the main influencing parameters that have to be considered, and the suitable equipment and
53 methodologies for the measurement in urban contexts.

54 To fill these gaps in the literature, the present study carried out a wide analysis of the cooling effect due to
55 the evapotranspiration process on green roofs. The scope of this paper includes the analysis and discussion of
56 the following topics: the main equipment and methodologies used to measure the ET in green roofs, the

57 correlation between evapotranspiration and the energy performance of green roofs, the main experimental
58 results from the literature and the physical-mathematical models used to calculate the latent heat flux on
59 green roofs. Furthermore, this paper provides an exhaustive review of the main influencing parameters of ET
60 in green roofs and their classification according to the potential evapotranspiration capacity.

61 However, due to the high number of studies carried out on green roofs, this review is focused on the research
62 that expressly evaluate experimentally or analytically the evapotranspiration process in green roofs.
63 Therefore, all researches examining performance and benefits of green roofs without directly correlating
64 them with evapotranspiration is out of the scope of this study. In addition, the previous studies that have
65 evaluated the role of evapotranspiration in the hydraulic performance and water balance of green roofs, in
66 terms of storm water management and runoff of these systems, are not included in this review.

67 In order to organize the reviewed data and to facilitate the understanding thereof, paper is structured in seven
68 sections as follows: Section 2 provides a general description of evapotranspiration process, how it is defined,
69 what does it depends on and how it can be determined. Section 3 and 4 show the main climatological
70 parameters and characteristics of vegetation and substrate that influence the ET of green roofs, respectively.
71 Section 5 describes the principal experimental measurement methods used to evaluate the evapotranspiration
72 of green roofs, the results obtained from them and a summary of the different units of measurement used.
73 Section 6 describes the mathematical models that take into account the latent heat within a green roof energy
74 balance and their main outcomes. In section 7, the main findings derived from research performed using
75 dynamic simulation software are reported. Finally, Section 8 presents the sensitivity analysis conducted by
76 previous studies to determine the influence of the different parameters (volumetric water content, solar
77 radiation, wind velocity, relative humidity, soil thickness, etc.) on the evapotranspiration effect.

78

79 **2. An overview of evapotranspiration in green roofs**

80 During recent years, evapotranspiration (ET) has received a growing interest from the green roof research
81 community because of its impact on heat and mass transfer. This phenomenon is a combination of the water
82 transpired by plants during their growth or retained in the plant tissue (transpiration) plus the moisture
83 evaporated from the soil surface and vegetation (evaporation). On one hand, **transpiration** is the process by

84 which moisture is carried through plants from roots to small pores on the underside and upper side of leaves,
85 where it changes to vapour and is released to the atmosphere. Transpiration is essentially evaporation of
86 water from plant leaves. Transpiration also includes a process called guttation, which is the loss of water in
87 liquid form from the uninjured leaf or stem of the plant, principally through water stomata. On the other
88 hand, evaporation is the process whereby liquid water is converted into water vapour and is removed from
89 the soil surface. It is the only form of moisture transfer from land and oceans into the atmosphere. These
90 processes are mainly determined by solar irradiation reaching the soil surface as it supplies the necessary
91 energy.

92 The level of the plant development has a considerable influence on the rate of water consumption and in the
93 final energy balance of a green roof system. During the development of complete vegetative cover, the water
94 consumption rate increases rapidly from low to high values. When plants are small, water is mainly lost by
95 evaporation from the soil; later, once the vegetation is well developed and completely covers the soil surface,
96 transpiration becomes the main process. However, the experimental data revealed that ET has a dynamic and
97 complex behaviour that depends on both climatological parameters and soil and vegetation characteristics
98 [32,33].

99 The principal climatological parameters to assess the ET process are: the solar radiation, the wind speed, the
100 air temperature, the relative humidity, and the sky conditions. In addition, ET also depends on the
101 characteristics of both vegetation and soil, principally the degree of shading of the canopy (leaf area and
102 density, LAI) and the amount of water available at the soil surface. In particular, the characteristic of the
103 vegetation that is most important from the standpoint of impacts on the heat transfer through the roof is the
104 leaf area index (LAI). LAI is established as the one-sided green leaf area per unit ground surface area ($LAI =$
105 $leaf\ area/ground\ area, m^2/m^2$) in broadleaf canopies. The LAI value depends on the type and the growth
106 phase of the plant (crop), usually ranging from 0 to 10. E.g., if the average parcel of roof surface is beneath
107 two leaves, the corresponding LAI is 2. Values of LAI for green roofs vary depending upon plant type, but
108 are typically in the range of 0.5–5.0 [34]. Moreover, the stomatal resistance, the plant height, the
109 development of the vegetation and the transpiration rate of each plant species, determine the aptitude to
110 transfer moisture near to the surface roots and canopy, consequently, these characteristics have also influence
111 on the ET rate.

112 When rain and irrigation are scarce, the water content in the substrate drops and the soil surface dries out.
 113 Thereby, in the absence of water supply the evapotranspiration decreases rapidly and may cease almost
 114 completely within a few days.

115 Table 1 summarizes the climatological and green roof parameters affecting evapotranspiration.

116 *Table 1 Climatological and green roof parameters affecting ET*

Climatological	Canopy	Soil	Management practice
Solar radiation	Degree of shading	Water content	Irrigation regime
Air temperature	Canopy characteristics	Soil characteristics	Cultivation practice
Air humidity	Canopy development		
Wind speed			
Rain			
Sky condition			
Season			

117
 118 The evapotranspiration rate can be obtained by experimental measurements or by means of modelling
 119 approaches. Specific devices and accurate measurements of various physical parameters, or the soil water
 120 balance, are required to determine evapotranspiration.

121 The lysimeter is one of the most widely used equipment to measure evapotranspiration. Such device is made
 122 of a soil volume covered by plants placed in a container hydrologically separated by the surrounding soil.
 123 Lysimeters can be classified as non-weighing and weighing type. The weighing lysimeter is based on the
 124 principle of the mass continuity. The evapotranspiration (ET), expressed in mm, is calculated by Eq. 1 as the
 125 difference among precipitation (P), drainage (D), superficial runoff (O) and the variations in soil water
 126 storage (ΔS) (Figure 1).

127
$$ET = P - D - O \pm \Delta S \quad (1)$$

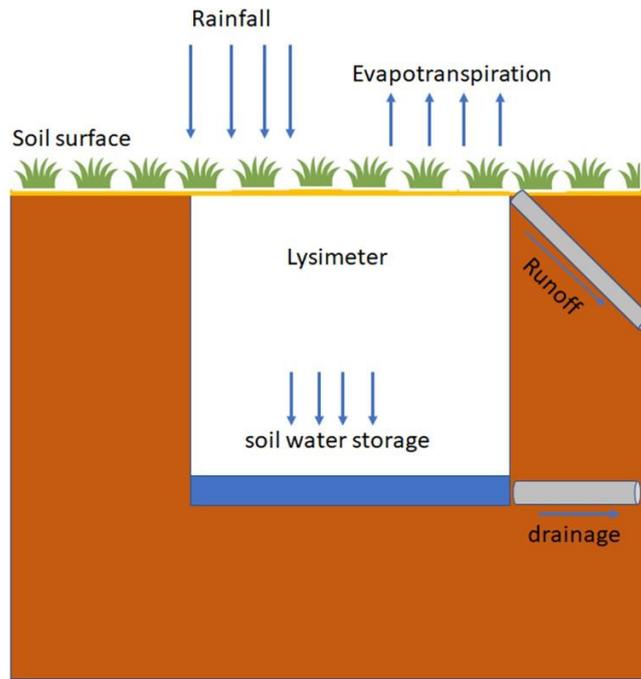


Figure 1 Schematic representation of the soil water balance in weighing lysimeter

128

129

130

131 Weighing lysimeters provide the direct measurements of evapotranspiration over time by monitoring the
 132 evolution of the tray weights (change of mass) due to the water losses. As regard the variation of water
 133 stored (ΔS), it is determined through measurement of the weight change of the soil column over time, with
 134 an accuracy of few hundredths of millimetres. Usually the following equivalence is assumed: $1 \text{ kg} \approx 1 \text{ L m}^{-2}$
 135 $= 1 \text{ mm}$.

136 Non-weighing lysimeters allow determining the evapotranspiration, during a given time period, subtracting
 137 the drainage water collected at the bottom of the lysimeters from the total water input. Actually, few studies
 138 directly quantified ET by measuring the rate of water loss [35], since such method is often expensive and
 139 demanding in terms of accuracy of measurements.

140 In order to predict the evapotranspiration, therefore, numerous numerical methods have been developed
 141 based on climatological data (e.g. temperature, day length, humidity, wind, and solar irradiance) [36]. These
 142 numerical models, such as those of Hargreaves and Allen (2003) [37], Priestley and Taylor (1972) [38],
 143 Penman (1948) [39], and Penman–Monteith [40,41], estimate the so called “potential evapotranspiration”
 144 (PET or ET_0) over bare soil surface or vegetation.

145 Penman (1948) defined PET as the ET from actively growing short green vegetation, completely shading the
 146 ground and never suffering scarcity of moisture availability. Consequently, PET models neglect factors that,

147 conversely, are decisive in the actual evapotranspiration (AET) that occurs under natural field conditions
 148 (i.e., variable soil water contents).

149 Table 2 summarizes the most common models used to evaluate ET. All these previous models are
 150 characterized by a daily time step.

151 *Table 2 Models for estimating evapotranspiration*

Name	Function	Reference
Penman-Monteith (1965)	$ET = \frac{0.408 \Delta (R_n - G) + \frac{\gamma^{900}}{T_a + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)}$	[39]
Priestley-Taylor (1972)	$ET = \alpha \Delta (R_n - G) / (\Delta + \gamma)$	[38]
Hargreaves (1975)	$ET_0 = 0.0075 R_s T_F$	[37]
Hargreaves (1985)	$ET_0 = 0.0022 R_s (T_a + 17.8) TD^{0.5}$	[37]
FAO-56 Penman-Monteith (1998)	$ET_0 = \frac{0.408 \Delta (R_n - G) + \gamma \frac{\gamma^{900}}{T_a + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)}$	[41]
Penman-Monteith ASCE (2005)	$ET_{sz} = \frac{0.408 \Delta (R_n - G) + \gamma \left(\frac{C_n}{T_a + 273} \right) u_2 (e_s - e_a)}{\Delta + \gamma (1 + C_d u_2)}$	[40]

152
 153 The most known PET model is the Penman-Monteith, which allow estimating the latent heat fluxes at the
 154 vegetation layer that achieve the daily evapotranspiration in a time step, taking into account numerous
 155 physical phenomena and some characteristics of the plants [42]. However, existing evapotranspiration
 156 models have substantial errors for hourly ET predictions over a range of moisture conditions to assess the
 157 hydrological performance of the green roofs during storm events. Therefore, Jahanfar et al. (2018) [43]
 158 developed a modified Penman-Monteith equation to provide improved prediction of hourly
 159 evapotranspiration specifically for green roof applications.

160 Alternatively, the indirect methods calculate the ET through the energy and mass balance equations [44,45].

161 The energy budget method (EBM) is based primarily on the concept that ET is function of the availability of
 162 energy to evaporate water (Q_{ET}), under the hypothesis that the moisture supply is not restricted.

163

164 3. Climatological parameters influencing ET

165 The principal meteo-climatic parameters affect the ET by removing water from the plants and soil surface
 166 are solar radiation, wind speed, relative humidity and air temperature, and sky conditions (e.g. cloudy,

167 sunny). These climatic features have both seasonal and geographic variations.

168 3.1. *Solar radiation and seasonal variation*

169 The water depletion rate of soil reflects the solar radiation input that sustains the evapotranspiration.
170 Tabares-Velasco and Srebric (2012) [46] performed a sensitivity analysis in order to understand which
171 parameters greatly affect ET. Among all the environmental variables, solar radiation was the one with the
172 strongest influence on ET. However, ET intensity varies due to the combined effect of solar radiation with
173 the other meteo-climatic parameters.

174 Jim and Tsang (2011) [47] found that the transpiration rate peaked in autumn due to the high level of solar
175 radiation and the low relative humidity. The actual solar radiation reaching the earth surface depends by the
176 turbidity of the atmosphere and the presence of clouds, which reflect and absorb a large percentage of the
177 radiation. Therefore, sky conditions affect ET, since they modify the energy balance of the evaporating
178 surface.

179 Coutts et al. (2013) [48] evaluated the advancement of ET for both a green roof and a bare soil measuring the
180 volumetric water content during four clear sunny summer days. In both vegetated and bare soil, the ET was
181 rather modest, with values of about 50 W/m^2 , suggesting that during the monitored summer period there was
182 scarcity of water available in the soil to support evapotranspiration. Consequently, the cooling effect of the
183 green roofs was significantly restricted. Jim and Peng (2012) [49] differentiated the sky conditions into three
184 types: sunny, cloudy and rainy. Overall, sunny days registered progressive water loss from the substrate due
185 to evapotranspiration, while during cloudy days the evapotranspiration was low so the water was maintained
186 in the substrate. Moreover, the ET was correlated with the volume of water contained in the substrate,
187 distinguishing between moist and dry substrates. For each weather type, wet means that the moisture content
188 is at or near the maximum daily initial moisture level; moist means at or near the average daily initial
189 moisture level; and dry means at or near the minimal daily initial moisture level. Thus during cloudy days
190 both moist and dry substrate recorded similar evapotranspiration, while during sunny days the dry substrate
191 recorded an even higher evapotranspiration than the moist.

192 Otherwise, Lazzarin et al. (2005) [50] compared the ET in dry and wet soil in summer and observed that the
193 wet soil gave rise to higher evapotranspiration whereas in dry conditions that contribution was limited. In

194 winter, despite the considerably lower solar irradiance in comparison to the summer season, the
 195 evapotranspiration flux was also appreciable. During summer, with the soil in almost dry conditions the
 196 green roof allowed an attenuation of the thermal gain entering the underneath room of about 60% with
 197 respect to a traditional roofing with an insulating layer. During the winter the evapotranspiration process was
 198 driven above all by the air vapour pressure deficit; it is not negligible weight produced an outgoing thermal
 199 flux from the roof that was 40% higher than the corresponding one of a high solar absorbing and insulated
 200 roofing.

201 Jim and Tsang (2011) [47] found that the seasonal transpiration rates on sunny days were, in descending
 202 sequence: autumn, summer, winter and spring. They suggested that the relatively high transpiration rate
 203 observed in summer sunny days occurs because high solar radiation and air temperatures promote
 204 photosynthesis. In winter sunny days, the transpiration rate was lower than in autumn and summer because
 205 of the solar radiation is less intense. Such result was confirmed by the modest transpiration rate observed in
 206 spring, the lowest recorded in this study, which were due to weak solar radiation and low temperatures
 207 characterizing this season.

208 *In the study performed by Lee and Jim (2018) [51], the progressive dropping of air and green roof surface*
 209 *temperatures in the course of the sunny day was explained by the effective cooling brought by*
 210 *evapotranspiration fuelled by solar radiation input. Even though irradiance at the green roof surface was*
 211 *limited, the ambient warmth and relatively low surface temperature did not require a lot of latent heat*
 212 *absorption to cool down.*

213 As shown in Table 3, most of the analysed studies evaluated ET during summer periods when it is expected
 214 to be higher in comparison to winter periods, due to the influence of solar radiation and relative humidity.
 215 Since sky conditions influence on the final ET process, it is important to highlight the scarce literature (6
 216 over 21) that provide a proper description of the weather conditions.

217 *Table 3. Classification of the studies reviewed according to the season, sky conditions and climate classification*

References	Köppen classification	Weather	Season	Type of study
Feng et al. [52]	Cfa	-	Summer	Modelling
Jim and Peng [49]	Cwa	Sunny-cloudy-rainy	Summer	Experimental
Jim and Tsang [47]	Cwa	Sunny-cloudy-rainy	Whole year	-
Lazzarin et al. [50]	Cfa	-	Summer-winter	Modelling
He et al. [53]	Cfa	Clear-cloudy-rainy	Summer	Modelling
Tabares-Velasco and Srebric [54]	-	-	Summer	Experimental

Tabares-Velasco and Srebric [46]	-	-	Summer	Modelling
Ouldboukhitine et al. [55]	Cfb	-	Summer	Experimental
Coutts et al. [48]	Cfb	Sunny	Summer	Experimental
Schweitzer and Erell [56]	Csa	-	Summer-winter	Experimental
Ouldboukhitine et al. [57]	Cfb	-	Summer	Experimental
Tan et al. [58]	Af	-	Summer-winter	Experimental
Tian et al. [59]	Cfa	-	Summer	Modelling
Hodo-Abalo et al. [60]	-	Sunny	-	Modelling
Tsang and Jim [61]	Cwa	Sunny-cloudy	Summer	Modelling
Ouldboukhitine et al. [62]	-	Sunny	Summer	Modelling
Boafo et al. [63]	Dwa	-	Summer-winter	Simulation
Silva et al. [64]	Csa	-	Summer-winter	Simulation
Vera et al. [65]	Bsk			
	Csc	-	Summer	Simulation
	Cfb			
Lee and Jim [51]	Cwa	Sunny-cloudy-rainy	Summer	Experimental

218

219 The previous survey **indicates** that the solar radiation is the climatic data with the strongest correlation with
220 evapotranspiration [49]. Such correlation will be further analysed in Section 8, assessing previous sensitivity
221 analyses.

222 Otherwise, since the ET phenomena depends also by the whole meteo-climatic features, future studies have
223 to include as much possible complete meteo-climatic description in order to correlate the ET with the main
224 climatic conditions (e.g. sunny, cloudy and rainy days). Furthermore, because of the lack of studies that
225 cover the ET during an entire year, further experimental studies should include a whole year analysis in order
226 to evaluate the ET in the different seasons and in different weather conditions.

227 3.2. Wind speed

228 The process of vapour removal also depends by the air turbulence, which increase the convective heat fluxes
229 between the atmosphere and the soil surface, as well as the airflow over the soil surface. Continuous
230 vaporization of water by means of ET leads the air above the soil surface to become gradually saturated. If
231 this vapour is not continuously replaced with drier air, the driving force for water vapour removal and ET
232 decrease. Intense wind improved the transport not only of heat but also of water vapour, increasing the
233 evapotranspiration fluxes.

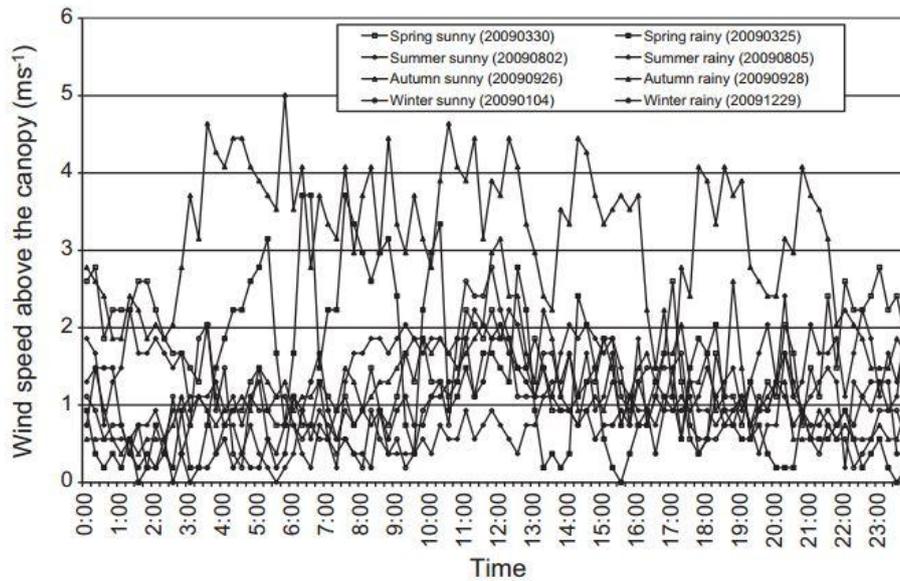
234 Schweitzer and Erell (2014) [56] compared the total daily evapotranspiration for four plant species during
235 days with weak ($2 \text{ m}\cdot\text{s}^{-1}$) and strong wind ($5 \text{ m}\cdot\text{s}^{-1}$). The authors concluded that there were substantial
236 differences among the plant species, i.e. the vegetated roof with *Aptenia* losing less than half as much water

237 as the vegetated roof with *Halimione*, about $3.0 \text{ L}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ compared to $7.5 \text{ L}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ under low wind
238 conditions ($2 \text{ m}\cdot\text{s}^{-1}$). This rate was even less than for exposed moist soil, i.e. without plants, about 3.8
239 $\text{L}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$. The other two species analysed, *Pennisetum* and *Sesuvium*, reached intermediate value, about
240 $7.0 \text{ L}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$. In windy conditions ($5 \text{ m}\cdot\text{s}^{-1}$), the maximum hourly loss for *Pennisetum* was nearly 2.0
241 $\text{L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$, and the daily total was over $9.0 \text{ L}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$. *Sesuvium*, moist soil, *Aptenia* and *Halimione* reached
242 lower values of evapotranspiration, 8.8 , 6.0 , 5.8 and $4.0 \text{ L}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$, respectively. In this study, high wind
243 speed enhanced the ET.

244 In another experiment, Tabares-Velasco and Srebric (2011) [54] found that when the wind speed varied from
245 $0.1 \text{ m}\cdot\text{s}^{-1}$ to $1.0 \text{ m}\cdot\text{s}^{-1}$ the evapotranspiration rate increased from 10% to 30%. This result confirm that air
246 convection effectively brings water vapour from the soil or foliage to the atmosphere increasing the
247 evapotranspiration rate.

248 For instance, an increase of the convection coefficient, which has a direct correlation with wind velocity,
249 from 12.0 to $16.0 \text{ W}/\text{m}^2\text{K}$ reduce the heat storage by 24% and 45% for bare and green roofs, respectively
250 [61].

251 Jim and Tsang (2011) [47] found a rather modest correlation between the wind above the canopy and
252 transpiration, so the wind should not play a major role in facilitating the transpiration rate. Figure 2 shows
253 the sunny and rainy wind speed measured at canopy top in [47]. The wind speed was relatively higher on
254 rainy days than on sunny ones. The wind speed on rainy and sunny days averaged at 3 ms^{-1} and 1 ms^{-1}
255 respectively. The correlation coefficients between wind and transpiration at -0.1 to 0.1 ($p \leq 0.05$) was
256 weak. Although wind speed was higher on rainy days, the associated high relative humidity suppresses
257 transpiration.



258
259 *Figure 2. Seasonal and diurnal wind speed above the canopy of the sky woodland [47]*

260 **3.3. Relative humidity and air temperature**

261 Even if the energy supplied by the **solar radiation** is the main driving force for the vaporization of water, the
262 difference between the water vapour pressure at the soil and plants surface, and the surrounding air are other
263 important factors that also determine the vapour removal.

264 High temperatures combined with lower relative humidity (RH) enhance the evapotranspiration process [66].
265 Tabares-Velasco and Srebric (2012) [46] stated that ET was strongly influenced by the environmental
266 conditions, in terms of air temperature and relative humidity in the vicinity of the green roof.

267 Generally, during night-time the outdoor air reach low temperatures that conversely cause the increase of RH
268 until 100%, so reducing the ET process. On the contrary, during day-time the higher air temperature induces
269 a fall of RH so allowing the evaporative process to take place [49].

270 **In a Cwa climatic area where the relative humidity and the air temperature varied between 50%, 23 °C in**
271 **autumn, and 80%, 36 °C in summer, Jim and Tsang (2011) [47] found that the highest transpiration rate is**
272 **observed in autumn rather than in summer, because of low relative humidity and mild air temperature.**
273 **According to this study, evapotranspiration is minimized in a humid environment and the high relative**
274 **humidity is the crucial factor that dampens the transpiration rate.**

275 **Unlike the green roof in the temperate region, the experiment carried out by Jim and Tsang [47] showed that**
276 **the transpiration rate of an intensive green roof in the humid-subtropical region, dominated by the Monsoon**
277 **climate system, depends mainly on photosynthetically active radiation and relative humidity.**

278 As with all the other processes that take advantage of evaporation, planted roofs do not have much to offer in
 279 terms of ET rate in a humid environment compared with an arid one [50].

280 *3.4. Irrigation regime*

281 Azeñas et al. (2018) [67] analysed the relationship between irrigation regime and heat flux through green
 282 roofs. In particular, the authors considered well-watered and water-limited condition. Surface drip irrigation
 283 at 50% and 25% of potential evapotranspiration (ET_0) was applied twice a week during the calculated time
 284 according to the nominal drippers flow (2 l h^{-1} for each dripper) and considering the number of drippers (9
 285 drippers for each module). Results showed lower heat flux in water-limited than in well-watered treatments
 286 in both non-vegetated and vegetated modules, suggesting that the lower heat transfer with air in comparison
 287 to water would counteract the cooling effect of evapotranspiration that is supposed to be higher in the well-
 288 watered modules, where the volumetric water content is higher. In particular, water-limited irrigation
 289 treatment was shown to increase the thermal insulation capacity when compared to complete well-watered
 290 irrigation treatment, by reducing the total transferred heat between 25% and 71% along the different seasons
 291 of the year, suggesting that the air/water substrate content has a greater effect on insulation than
 292 evapotranspiration.

293 *3.5. The geographic area*

294 The review conducted by Pérez et al. (2014) [68] concluded that the Köppen climate classification is the
 295 most suitable reference to compare research results about green infrastructures. In order to provide a
 296 continuous framework in the literature, this review used the same climate classification for all the reviewed
 297 papers (Table 4).

298 *Table 4. Climate classification of experimental, modelling and simulation studies*

Ref.	Authors	Year	Location		Climate according to the author	Köppen classification
[49]	Jim and Peng	2012	Hong Kong	Hong Kong	Humid-subtropical	Cwa
[69]	Takebayashi and Moriyama	2007	Japan	Kobe	-	Cfa
[54]	Tabares-Velasco and Srebric	2011	USA	Pennsylvania	-	Dfb
[46]	Tabares-Velasco and Srebric	2012	USA	Pennsylvania	-	Dfb
[55]	Ouldboukhitime et al.	2012	France	La Rochelle	-	Cfb
[48]	Coutts et al.	2013	Australia	Melbourne	-	Cfb

[56]	Schweitzer and Erell	2014	Israel	Tel Aviv	Mediterranean	Csa
[57]	Ouldboukhitime et al.	2014	France	La Rochelle	-	Cfb
[58]	Tan et al.	2017	Singapore	Singapore	-	Af
[52]	Feng et al.	2010	China	Guangzhou	-	Cfa
[70]	Djedjig et al.	2012	France	La Rochelle	-	Cfb
[69]	Takebayashi and Moriyama	2007	Japan	Kobe	-	Cfa
[50]	Lazzarin et al.	2005	Italy	Vicenza	-	Cfa
[53]	He et al.	2016	China	Shanghai	North subtropical monsoon	Cfa
[46]	Tabares-Velasco and Srebric	2012	USA	Pennsylvania	-	Dfb
[59]	Tian et al.	2017	China	Chongqing	Humid subtropical monsoon	Cfa
[60]	Hodo-Abalo et al.	2012	Togo	-	-	Aw
[61]	Tsang and Jim	2011	Hong Kong	Hong Kong	-	Cwa
[62]	Ouldboukhitime et al.	2011	France	La Rochelle	-	Cfb
[63]	Boafo et al.	2017	Republic of Korea	Incheon	Humid continental	Dwa
[64]	Silva et al.	2016	Portugal	Lisbon	Mediterranean	Csa
			USA	Albuquerque	Semi-arid	Bsk
[65]	Vera et al.	2017	Chile	Santiago	Semi-arid	Csc
			Australia	Melbourne	Marine	Cfb

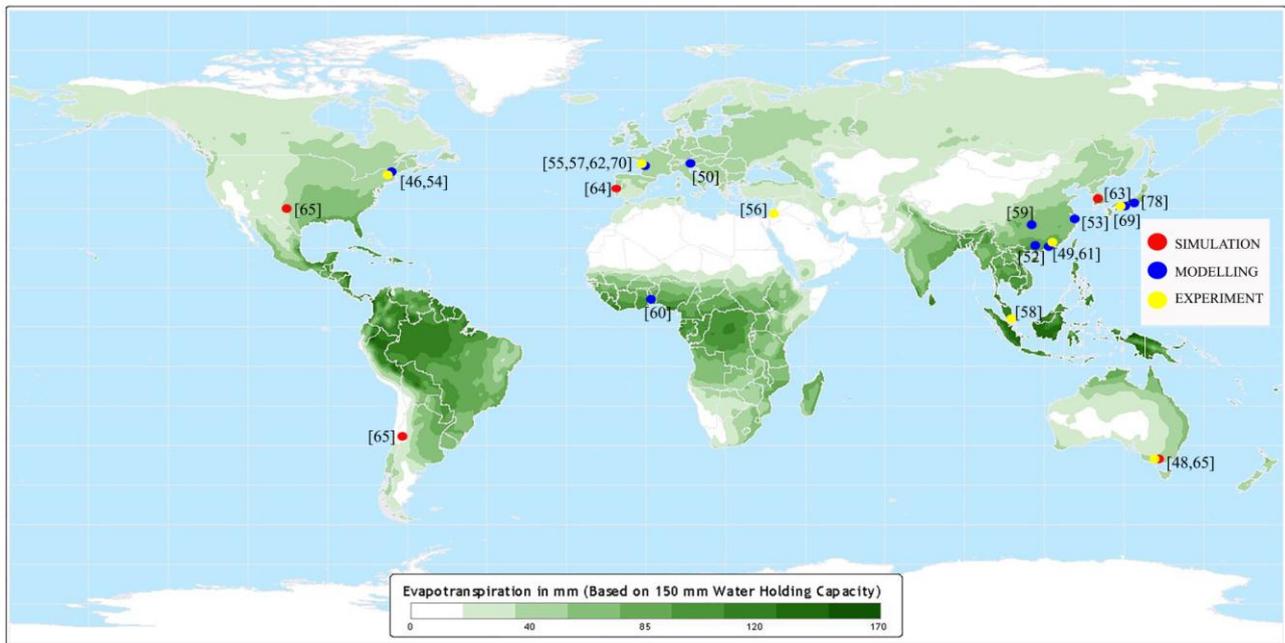
299

300 Most of the studies reviewed in this paper (71%) were carried out considering temperate climatic conditions,
 301 first letter C according to the Köppen classification. About 17%, 8% and 4% of the studies were developed
 302 in tropical (D), arid (A) and cold climates (B), respectively.

303 The 71% of the studies performed in temperate climates are located in areas without dry seasons (Cf
 304 according to the Köppen classification). About 17% of these studies were performed in climates with dry
 305 summers, second letter s (Cs according to the Köppen classification). Finally, only a few of the studies
 306 analysed, about 12%, are located in climates with dry winters, second letter w (Cw according to the Köppen
 307 classification).

308 Figure 3 shows the analysed studies located on the world evapotranspiration map. **The Water Holding**
 309 **Capacity is the total amount of water available for plants that is held against gravity in a soil and is usually**
 310 **estimated as the amount present at -0.03 MPa average water potential minus the amount present at -1.5 MPa**
 311 **water potential. In [71], the authors stated that it is a very important soil characteristic strongly and positively**
 312 **correlated to the inherent productivity of soils.**

313 Most of the studies were performed in the western part of the world under temperate climatic conditions
 314 (Figure 3). However, other regions could allow achieving high rates of ET that have not yet deeply explored
 315 or at least there is a lack of data in literature. Consequently, future studies should encompass experimental
 316 study in tropical and arid climates where green roofs could enhance the cooling effect on buildings thanks
 317 the potential high ET rates.



318
 319 *Figure 3. Location of simulation, modelling and experiment studies in the world Evapotranspiration map [72]*

320
 321 However, it has to be underlined as in hot arid regions green roofs need to be well watered, due to the
 322 abundance of solar energy and dry air, consequently they consume large amounts of water. On the other
 323 hand, in humid tropical regions, since the air is frequently close to saturation, less additional water can be
 324 transferred from the green roof to the atmosphere, and hence the evapotranspiration rate is lower than in arid
 325 regions.

326 The world evapotranspiration map presented in Figure 3 is obtained by considering all the environmental
 327 parameters of a specific geographic area affecting natural evapotranspiration, such as solar radiation, relative
 328 humidity, annual average temperatures and annual average precipitation, which are the most important
 329 parameters for the vegetation development.

330 In some geographic areas of the world presented in Figure 3, such as in the African desert area, where
 331 potential evapotranspiration is high due to solar radiation and air temperatures, there is no evapotranspiration
 332 due to the lack of water. Therefore, if there were enough amounts of natural water (e.g. rain and water wells),

333 these geographic areas could be enabled to take advantage of the cooling effect of green roofs.

334 An analysis of Figure 3 underlines that further experimental studies about ET should be carried out in
335 regions of the world that have not been yet deeply investigated.

336 It is worth mentioning that the ET in green roofs differs from the phenomenon of natural evapotranspiration
337 since, in addition to the above-mentioned climatic variables, it is also affected by the inherent properties of a
338 green roof system. Some of these properties are; type of plants, substrate characteristics (thickness and
339 composition), and irrigation regime that provides water for evapotranspiration in the absence of precipitation.

340

341 **4. Plant-substrate parameters influencing ET**

342 *4.1. Volumetric water content*

343 The cooling performance of a green roof depends on the water content of the substrate that determines the
344 availability of water for evapotranspiration. Volumetric water content in the soil is related to the green-roof
345 hydrological cycle because the green roof gains water from rainfall and irrigation, and loses it through
346 evapotranspiration, surface runoff and drainage.

347 Djedjig et al. (2012) [70] found that when the green roof was characterized by a VWC in the soil of 10% of
348 the maximum value, evapotranspiration was reduced to its minimum. On the contrary, evapotranspiration
349 increased when the substrate had high water content.

350 Jim and Peng (2012) [49] found that during rainy days, antecedent VWC in the soil reduces the infiltration
351 rate, thus increasing the runoff quantity. On successive sunny or cloudy days when drainage and run-off are
352 negligible, the water stored in the substrate depends by irrigation and evapotranspiration. Previous studies
353 [27,73,74] identified volumetric water content in the soil as the key factor for the evapotranspiration process,
354 especially when irrigation is not present. In Bevilacqua et al. (2015) [75] even though the environmental
355 conditions would allow evapotranspiration to take place, no considerable ET was found due to the limited
356 water content in the substrate.

357 In the research conducted by Tan et al. (2017) [58] on conventional garden soil and artificial substrates,
358 consisting mainly of perlite, the evapotranspiration rates exhibited strong positive correlations with the
359 volumetric water content. In fact, when volumetric water content in the soil decreased gradually, the plant

360 evapotranspiration rate was restricted. In addition, the ET decreased because of the low plant transpiration
361 activity due to the lack of available water even if high solar irradiance occurred.

362 The use of a water retention layer below the green roof substrate makes it possible to maintain the VWC
363 consistently higher. The water retention layer, therefore, sustains plant life by providing an additional
364 availability of moisture, i.e. a liquid such as water in the form of very small drops, either in the air, in a
365 substance, or on a surface. In green roof systems planted with *Sedum mexicanum* and *Disphyma austral*,
366 Voyde et al. (2010) [35] observed a rapid water loss via latent heat flux in the days after watering. This water
367 loss gradually decreased because the water available was reduced until plants stopped transpiring to preserve
368 water.

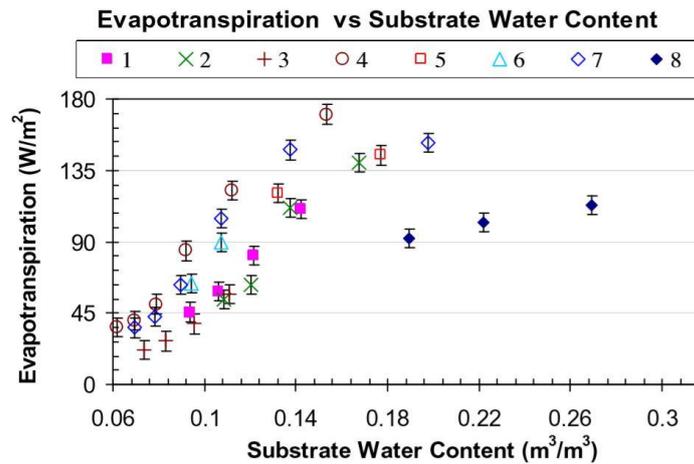
369 The sensitivity test performed by Feng et al. (2010) [52] has shown that an increase from 30% to 60% in
370 volumetric water content in the soil showed a reduction of 24% the heat stored within the green roofs, thanks
371 to the increasing latent heat. On the contrary, Tabares-Velasco and Srebric (2012) [46] found that the water
372 content in the substrate did not have the most significant impact on ET. However, a change in substrate
373 conditions from the driest to the wettest led to a decrease in the substrate temperature of about 10.0 °C and a
374 reduction in the incoming heat flux by 40%. This reduction was mainly due to an increase in the
375 evapotranspiration rate (from 8.0 to 230.0 W/m²) despite of an increase of 70% in substrate thermal
376 conductivity and a decrease of 50% in substrate reflectivity, measured with a Portable Spectroradiometer
377 using a calibrated lamp different that the fluorescent lamps directly above plants. **Soil reflectivity depends on
378 soil type and water content that typically varies from 0.10 for wet soil to 0.35 for dry soil.**

379 **He et al. (2017) [76] found that a higher water ratio helped to increase the evapotranspiration intensity while
380 it decreased the thermal resistance of soil layer.** As it was evaluated in some studies, the relation between the
381 increment in the substrate volumetric water content and the increment of ET was not linear [49,54].

382 Evapotranspiration-substrate water content curves have an elongated “S” shape with low evapotranspiration
383 rates when water is scarce in the substrate and high evapotranspiration rates when water is abundant. In the
384 middle of the substrate water content range, the relationship is approximately linear (Figure 4). Experimental
385 data revealed that samples with higher water content provided higher latent fluxes and lower convective
386 fluxes [52].

387 As result this section highlight that substrate water content plays an important role in decreasing

388 temperatures on the green roof surface and the total incoming heat flux through the roof.



389
390 Figure 4. Relationship between evapotranspiration and substrate water content [54]

391

392 4.2. Vegetation

393 The transpiration process of plants contributes to the evaporation from the substrate, moreover the plant layer
394 shades the roof surface and further reduces the heat fluxes incoming into the roof.

395 The species of plants, their physiology and growth typology, influence the green roof cooling effect by
396 means of the ET process. Succulent plants, which store excess water in their thick leaves, are generally well
397 adapted to extreme climates, and particularly in dry conditions. The *Sedum* family, capable of activating
398 *Crassulacean Acid Metabolism* (CAM) photosynthesis, is recommended for extensive roofs where the depth
399 of the soil layer is very shallow [77]. Under dry soil conditions, the evapotranspiration in a green roof with
400 *Sedum* may be mostly evaporation from soil, with little transpiration from plants. Voyde et al. (2010) [35]
401 found that planted treatments of *Sedum mexicanum* and *Disphyma australe* attained a latent heat flux of 2.19
402 mm/day and 2.21 mm/day, respectively, when the plants were not water stressed. Irrigated green roofs
403 showed a latent heat flux higher than 200 W·m⁻², suggesting that despite the presence of drought-tolerant
404 *Sedum*, irrigation increased evapotranspiration when water was available.

405 Schweitzer and Erell (2014) [56] compared a well-watered roof covered with and without plants and
406 observed that ET was the least effective cooling mechanism without the shade provided by plants. *Aptenia*
407 lost less than half as much water as *Pennisetum*, about 3 L m⁻²day⁻¹ and 7 L m⁻² day⁻¹ respectively. The
408 *Pennisetum* loss rate was even less than in bare moist soil, about 3.8 L m⁻² day⁻¹. Coutts et al. (2013) [48]
409 evidenced that soil without plants may deliver greater latent heat fluxes, as the resistance to water loss from

410 the vegetation surface is not present. The peaks of latent heat flux afterwards a cycle of irrigation are lower
411 on the green roofs than the bare soil, this because the green roofs retained water in the substrate and
412 vegetation over a longer period. The samples with plants consistently show an average reduction of the heat
413 flux transferred into the spaces beneath the roof of about 25% compared to samples without plants. This is
414 because plants provide extra shading to the roof, additional water storage, and a better water control by
415 means of evapotranspiration and photosynthesis [54].

416 It was found that the Leaf Area Index (LAI) factor and the amount of evapotranspiration from the top surface
417 have a large effect on the heat flow transferred into the spaces beneath the roof [78]. In a Mediterranean
418 climate, results have shown that the LAI greatly influences the thermal performance of the vegetated roof
419 since it enhances shading, convective heat transfer, and evapotranspiration. Higher LAI values allow to
420 achieve higher cooling effect due to the increase of evapotranspiration [79,80].

421 Tabares-Velasco and Srebric (2012) [46] pointed out that among the green roof design variables, the most
422 significant factor that allowed a reduction in temperature and heat flux through the substrate was the LAI.

423 In agreement with the findings obtained by Tabares-Velasco and Srebric [62], Hodo-Abalo et al. (2012) [60]
424 found that evapotranspiration is more intense when the foliage is sufficiently dense. In addition, the LAI has
425 important effects on the energy phenomena in the vegetation layer, thanks to the shading and transpiration
426 that it provides, reducing solar flux penetration, stabilizing fluctuating values and reducing the indoor
427 temperature.

428 Theodosiou (2003) [66] revealed large heat flows from the substrate surface to the atmosphere for surfaces
429 on sunny days and relatively small flows on cloudy days, when the value of LAI was up to 3.0. Therefore,
430 under such operative conditions there was a significant increase the cooling effect on the room space. It was
431 an office building. The floor beneath the planted roof had an area of 70 m², internal gains of 1.10 kWh
432 during working hours (08:00–16:0 h) and 0.1 kWh during the rest of the day. The **air conditioning** functions
433 during the 8 h period with a thermostat set at 26 °C and.

434 **Lee and Jim (2018) [51] concluded that the dense foliage of the woodland vegetation should have provided**
435 **greater shading and evapotranspirative cooling than an Indian green roof with herbaceous vegetation but 0.4**
436 **m-deep substrate used by Kumar and Kaushik (2005) [81]. The green roof used in [51] achieved only half**
437 **the maximum air temperature of 12 °C on the Indian intensive green roof. The authors concluded that such**

438 disparity could be caused by variations in vegetation characteristics.

439 4.3. Stomatal resistance

440 Plant transpiration or latent heat flux depends on the physiological properties of the plants and their stomatal
441 resistance or conductance that controls water loss. Stomatal resistance is opposed to the transport of water
442 vapour and carbon dioxide to or from the stomata on the leaves of plants, the lower the value of stomatal
443 resistance, the greater the ET. It depends by the water content in the interior of the stomata cavity and on the
444 exterior surface of the leaf, but also by air density and moisture flux.

445 The dimension of stomatal resistance is time over distance that is the inverse of velocity, its values depend
446 on plant selection. Grass plants with stomatal resistance of $60 \text{ s}\cdot\text{m}^{-1}$ produce evapotranspiration fluxes that
447 are 3-4 times higher than those produced by succulent plants (e.g. *Sedum*) [46].

448 Generally, plant species with low values of stomatal resistance allow achieving higher ET if there is
449 sufficient water in the soil.

450 4.4. Stomatal conductance

451 Otherwise, the stomatal conductance gives an estimation of the rate of exchange of gases and transpiration
452 through the stomata of the plants, which depends by solar radiation, temperature, humidity and water
453 availability. Higher stomatal conductance tends to correspond to higher evapotranspiration rates. The
454 stomatal conductance is usual measured in $\text{mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.

455 Tan et al. (2017) [58] have studied the variation of the stomatal conductance of *Cyathula prostrata* in
456 function of both the cycle of irrigations and the type of soil (i.e. artificial soil, consisting mainly of perlite,
457 and normal garden soil), which is a commercially available soil mix commonly used in urban landscapes. It
458 was observed that during periods of regular irrigation, average stomatal conductance of *Cyathula prostrata*,
459 which is a creeping shrub, was about $600.0 \text{ mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. When irrigation was withheld, the stomatal
460 conductance of *Cyathula prostrata* planted into the artificial soil was reduced to around $100.0 \text{ mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$,
461 while in a normal garden soil the stomatal conductance was reduced to $50.0 \text{ mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. For the case of the
462 artificial soil equipped with a water retention layer, when irrigation was withheld the stomatal conductance
463 slightly reduced to $425 \text{ mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. When irrigation was resumed, stomatal conductance levels increased

464 to $375.0 \text{ mmol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ both in the case of artificial and normal garden soil.

465 This section has highlighted that the choice of the type of plants entails to different stomatal conductance,
466 which in turns affects the ET.

467 4.5. *The substrate and drainage layer*

468 Several studies [33,82,83] have revealed that the characteristics of the substrate and drainage layer affect the
469 evapotranspiration phenomena in the green roof.

470 The characteristics of the substrates that influence evapotranspiration are porosity, size of the soil particles,
471 compaction of the material and permeability (or hydraulic conductivity), as well as the thickness of the
472 material. Several studies have investigated the thermo-physical and hydrological properties of different types
473 of substrate [84,85], which could be constituted of both organic and inorganic material.

474 However, less attention was paid in assessing the impact of the drainage layer on the green roof
475 evapotranspiration, although the evapotranspiration varies considerably depending on the type of solution
476 adopted for the drainage layer. The most common solutions used as drainage layers in green roofs are
477 constituted by modular plastic panels with a water retention layer, or in alternative by natural granular
478 materials such as expanded clay, pumice, natural pozzolana, perlite, etc. Recently new granular materials
479 deriving, in whole or in part, from the recycling of materials have been proposed as drainage layer [86,87].

480 The benefits derived by the use of such materials are their low environmental impact, in terms of reduction
481 of natural resource consumptions in comparison to traditional drainage layer materials [88].

482 Regarding different types of substrates for green roofs, Tan et al. (2017) [67] have analysed the performance
483 of an artificial substrate characterized by a higher porosity compared to a garden soil, which drain water
484 faster than topsoil (natural soil). Hence, when irrigation was being withheld, less water was available for
485 transpiration or evaporation from the substrate. As consequences, lower volumetric water content and
486 evapotranspiration rates were experimented in this artificial soil compared to a normal garden soil.

487 Getter et al. (2011) [89] suggested that increasing substrate depth would allow the use of plants with greater
488 biomass and leaf area, leading to a higher latent heat flux. In the thin substrate of common extensive green
489 roofs, due to the limited substrate mass effect, solar energy heating the whole substrate increasing its
490 temperature, which in turn increase the evapotranspiration and the water depletion [49].

491 However, it has to be reminded that when the VWC decreases below specific threshold also the ET is
 492 reduced.

493 This section has highlighted how the substrate and the drainage layers affects the ET. Generally, artificial
 494 soil characterized by higher porosity drain water faster than topsoil (natural soil). Hence, when irrigation is
 495 withheld less water is available for transpiration or evaporation from the substrate.

496

497 **5. Equipment used in the reviewed green roof set-ups**

498 Evapotranspiration is difficult to measure in a direct way, since it is a complex physical-physiological
 499 phenomenon that depends on both the phase change of the water contained in the substrate and the
 500 physiological processes occurring in the plant species used in green roofs.

501 As a result, several studies [47,49,52,69,70] have estimated the evapotranspiration rate from plants and soil
 502 through data derived from the substrate water content (“indirect” measurements). Sensors located at different
 503 depths of the soil layer measured the volumetric water content (VWC). Other studies carried out by Lazzarin
 504 et al. (2005) [50], and He et al. (2016) [53] have used the volumetric water content in the soil to calculate the
 505 heat transfer model of green roofs.

506 Table 5 summarizes the main equipment used to evaluate ET and the monitoring periods adopted in literature
 507 studies reviewed. On one hand, the “indirect” measurements presented within this table refer to ET
 508 estimation using data derived from the substrate water content. In this case, the water content variation is
 509 assumed equal to the ET. On the other hand, “direct” measurements refer to ET estimation using data
 510 collected by a lysimeter or load cells, monitoring the evolution of sample weight and not the water content
 511 variation in the substrate.

512 *Table 5. Summary of the main instrumentation used in the reviewed set-ups and the length of monitoring periods*

References	VWC sensor	Load balance	Portable closed chamber	Indoor test	Outdoor test	Monitoring period	Type of measurements
[52]	X	-	-	-	X	11 days	Indirect
[49]	X	-	-	-	X	2 months	Indirect
[70]	X	-	-	-	X	3 weeks	Indirect
[69]	X	-	-	-	X	1 month	Indirect
[47]	X	-	-	-	X	1 day	Indirect
[50]	X	-	-	-	X	2 months	Indirect

[53]	X	-	-	-	X	2 weeks	Indirect
[90]	X	-	-	X	-	6 days	Indirect
[54]	X	X	-	X	-	2-6 days	Direct and indirect
[46]	X	X	-	X	-	2-6 days	Direct and indirect
[55]	-	X	-	X	-	7 days	Direct
[48]	X	-	X	-	X	4 days	Direct and indirect
[56]	-	X	-	X	-	1 day	Direct
[57]	-	X	-	X	-	Two days	Direct
[58]	X	X	-	-	X	2 months	Direct and indirect

513

514 The devices used for evaluating ET depend on the aim of the research. In fact, if the objective is to validate
515 an energy and mass balance model, researchers have frequently used volumetric water content sensors. On
516 the other hand, when the aim of the research consists in estimating the rate of evapotranspiration, high
517 precision scales combined with volumetric water content sensors are commonly used.

518 Most of the studies that used load cells were carried out in a laboratory (indoor test) set-up installing samples
519 with reduced size, while only a few studies evaluated ET directly in-situ (outdoor test)[48,58]. Finally, the
520 monitoring period varied widely, from one day to two months (see in Table 5). An important gap in the
521 literature review is detected since the duration of almost all experimental studies (12 over 16) do not provide
522 long periods of measurement (shorter than one month) that include the ET behaviour within the different
523 seasons of a specific climate. Only four studies [49,50,58,69] overcome the duration of a month period
524 monitoring. Besides the experimental set-ups of the following studies [46,50,52,70] were basically used for
525 validating numerical models, they also contributed in providing methodologies to evaluate ET at both levels,
526 theoretical and experimental.

527 In the following, a brief description of the different sensors and devices used for the ET measurement in
528 previous experimental studies is given.

529 Schweitzer and Erell (2014) [56] associated the water consumption in extensive green roofs to the ET
530 process, using mini-lysimeters. Ouldboukhitine et al. (2014) [57] evaluated the amount of water transpired
531 by the plants using wind tunnel to control the wind speed. The hydrologic transfer was measured using a load
532 cell installed under two green roof tray to track the weight loss due to water evapotranspired during the test.

533 The only difference between the two samples was that one of them was planted with vegetation and the other
534 without. While water was evapotranspired by the test trays with vegetation, it was only evaporated by the
535 tray without vegetation. The difference between the two trays allowed an estimation of the quantity of water
536 transpired by the plants. Ouldboukhitine et al. (2012) [55] measured the amount of water lost by
537 evapotranspiration and its impact on the prediction of water content variations using a setup to measure the
538 weight of trays suspended on the traction-compression sensor balance.

539 Liang Tan et al. (2017) [58] evaluated ET by using both direct (with load cell) and indirect methods (with
540 volumetric water content sensors). In such study, the authors divided green roof plots into three treatment
541 combinations characterized by different substrate type as well as the adoption of the water retention layer or
542 not. Sensors were embedded at 0.1 m depth in the middle planters in order to monitor volumetric water
543 content in the soil for each of the set-ups; then, evapotranspiration was measured by weighing the middle
544 planter box. Coutts et al. (2013) [48] used a portable closed-chamber to measure evapotranspiration rates
545 from green roof and soil without vegetation. With this method, chambers restrict the volume of air available
546 for the exchange between the surface and the atmosphere and the net emission or uptake of gases can be
547 measured as a change of water concentration. The latent heat flux, therefore, was determined from the
548 change in the mass concentration of water over time. Green roof samples were also instrumented with
549 volumetric water content into the soil probe at a depth of 0.08 m.

550 Ayata et al. (2011) [90], Tabares-Velasco and Srebric (2011, 2012) [46,54] evaluated evapotranspiration
551 rates by tracking continuously both, the variations in weight of the green roof sample with high-resolution
552 load cells, and the changes in the volumetric water content of the substrate. In these studies, the total water
553 loss measured with the water balance method were 10–20% larger than the load cell. Thus, the authors used
554 evapotranspiration data measured directly from the load cell to validate the heat transfer model proposed.

555 At the end of this survey, it is possible to observe that load cell is the most widely used device for assessing
556 in a direct way the evapotranspiration in green roofs. Thus, such equipment could be recommended in future
557 studies on ET.

558 *5.1. Units of measurement used for expressing the evapotranspiration rate*

559 The evapotranspiration rate is frequently expressed in millimetres (mm) per unit time. The rate expresses the
 560 amount of water lost from a cropped surface in units of water depth. Furthermore, the time unit has large
 561 variability, it can be assumed equal to an hour, day, ten-day period, month or even an entire growing period.

562 The evapotranspiration rate can be stated or in terms of the energy necessary for the water evaporation,
 563 namely the latent heat of vaporization (L_e), expressed in $\text{MJ m}^{-2} \text{ day}^{-1}$, or, using the lysimeter (load cell) to
 564 evaluate evapotranspiration by monitoring the evolution of the tray weights due to water loss over time,
 565 expressed the evapotranspiration in $\text{kg m}^{-2} \text{ day}^{-1}$.

566 Thus, a plethora of units of measurement are used to express evapotranspiration (mm, kg, W/m^2 , etc.), so it
 567 becomes rather complicate to compare the results obtained from different studies. Therefore, it could be
 568 useful to provide the conversion factors among the units of measurements used to characterize the
 569 evapotranspiration process in green roof.

570 Table 6 summarizes the conversion factors among the units of measurements used to express the
 571 evapotranspiration rate.

572 *Table 6. Conversion factors for evapotranspiration process measurement*

	Depth	Volume per unit area		Energy per unit area	Mass per unit area	Power per unit area
From \ To	mm day^{-1}	$\text{m}^3 \text{ ha}^{-1} \text{ day}^{-1}$	$\text{L m}^{-2} \text{ day}^{-1}$	$\text{MJ m}^{-2} \text{ day}^{-1}$	$\text{kg m}^{-2} \text{ day}^{-1}$	W m^{-2}
mm day^{-1}	1	10	1	2.45	1	28.36
$\text{m}^3 \text{ ha}^{-1} \text{ day}^{-1}$	0.1	1	0.1	0.245	0.1	2.836
$\text{L m}^{-2} \text{ day}^{-1}$	1	10	1	2.45	1	28.36
$\text{MJ m}^{-2} \text{ day}^{-1}$	0.408	4.082	0.408	1	0.408	11.57
$\text{kg m}^{-2} \text{ day}^{-1}$	1	10	1	2.45	1	28.36
W m^{-2}	0.035	0.35	0.035	0.0864	0.035	1

573 *5.2. Evapotranspiration rate carried out by literature studies*

574 Besides providing valuable technical details regarding the methods for measuring ET, experimental set-up
 575 tests also offer useful information on the real quantification of the ET process.

576 Liang Tan et al. (2017) [58] developed a study on both conventional garden soil, which is a commercially
 577 available soil mix commonly used in urban landscapes, and K-soil, which is a proprietary lightweight soilless

578 media, consisting mainly of perlite and organic matter. They found that evapotranspiration ranged between
579 2.0 and 7.0 kg m⁻² d⁻¹. Moreover, the authors also observed that plant evapotranspiration decreased
580 gradually in a similar manner to the corresponding soil water content, to approximately 2.0 kg m⁻² d⁻¹ in both
581 conventional garden soil and K-soil. On the contrary, evapotranspiration was around 4 kg m⁻² d⁻¹ when an
582 artificial soil, consisting mainly of perlite, was tested.

583 Other studies demonstrated that the evapotranspiration for trays with plants was always higher than the
584 evaporation of trays without vegetation [57], especially for trays using periwinkle (leafy plant) than for
585 ryegrass. In the periwinkle test, the water lost by evapotranspiration after 48 hours was 5.2 kg, about twice as
586 much as that lost only by evaporation that was about 3.0 kg. While the water loss was 3.5 kg after 48 hours
587 for the ryegrass sample.

588 A substantial variation of water loss among some plant species was found also in other literature studies. In
589 the tests performed by Schweitzer and Erell (2014) [56], *Aptenia* lost less than half as much water as
590 *Pennisetum*, about 3 L m⁻² day⁻¹ and 7 L m⁻² day⁻¹ respectively. The *Pennisetum* loss rate was even less than
591 in bare moist soil, about 3.8 L m⁻² day⁻¹. Ouldboukhitine et al. (2012) [55] measured that daily
592 evapotranspiration with a grass tray (2.34 mm) was greater than that with a *Sedum* tray (1.42 mm). The
593 cumulative evapotranspiration over three days was around 8.0 mm, 5.0 mm, and 4.0 mm for grass, *Sedum*,
594 and bare soil, respectively. These results are in contrast with those found by Coutts et al. (2013) in [48],
595 where the plants limited the ET. In addition, the daily evapotranspiration measured for grass (2.53 mm) is
596 greater than that calculated by the Penman-Monteith equation (1.66 mm). This difference is probably due to
597 the “tray factor”, as defined by Ouldboukhitine et al. (2012) in [55], and to the input parameters taken in
598 the Penman-Monteith equation such as temperature, aerodynamic resistance, and vapour pressure.

599 Some studies calculated the latent heat flux after measuring the quantity of water lost. In Coutts et al. (2013)
600 [48], the higher latent heat flux on soil (with maximum value about 280 W m⁻²) compared to green roof (with
601 maximum value about 210 W m⁻²) suggested that wet soil freely evaporated while evapotranspiration from
602 the green roof was limited by the lower surface temperatures and water uptake by vegetation. After
603 irrigation, there was a substantial increase in latent heat flux for both green roof and bare soil. Maximum
604 rates of latent heat flux increased on green roof and soil a mean of 100 W m⁻² and 90 W m⁻², respectively.

605 Other studies analysed the relationship between ET and different weather conditions. Jim and Peng (2012)

606 [49] evaluated both different typical days (sunny, cloudy, and rainy) and different substrate water content.
 607 The authors found that for a sunny day with moist soil, about 4.0 mm of water is extracted from the substrate
 608 to satisfy evapotranspiration (9.3 mm considering 5 mm due to irrigation). The water depletion during a
 609 sunny day with dry soil was 13.1 mm and it was notably higher in comparison to a sunny day with moist soil,
 610 despite the lower water content in the substrate. On the contrary, a cloudy day with limited solar gains and
 611 dry soil notably suffered a subdued depletion, at merely 5.8 mm.

612 Tabares-Velasco and Srebric (2012) concluded in their study [46] that the latent heat flux due to ET reached
 613 maximum values during the experiment with high wind speed, around 170 W m^{-2} , while minimum values
 614 occurred when there was low solar radiation, around 20 W m^{-2} . Takebayashi and Moriyama (2007) [69]
 615 found that the quantity of evaporation from the green surface in November, with maximum value of 0.06 g
 616 $\text{m}^{-2} \text{ s}^{-1}$, was higher than in August with maximum value of $0.02 \text{ g m}^{-2} \text{ s}^{-1}$.

617 In the study conducted by Tabares-Velasco and Srebric in (2011) [54], they observed that latent heat rates
 618 vary the substrate water content. The green roof sample achieved the largest and nearly constant
 619 evapotranspiration rates over 135 Wm^{-2} when VWC was above $0.14 \text{ m}^3 \text{ m}^{-3}$. Evapotranspiration decreased
 620 linearly with the VWC up to approximately $0.07 \text{ m}^3 \text{ m}^{-3}$, showing values between 135 and 45 Wm^{-2} .
 621 Evapotranspiration rates dropped in a nonlinear way when VWC was lower than $0.07 \text{ m}^3 \text{ m}^{-3}$ with values
 622 below 45.0 W m^{-2} . The daily evapotranspiration ratio was about 3.0 when the substrate was wet, with 20.0
 623 and 60.0 W m^{-2} latent heat flux during night and day respectively, while the day/night ratio was about 5.0
 624 when the substrate is dry, with 50.0 and 150.0 W m^{-2} latent heat flux during night and day, respectively.

625 Since the presented results about evapotranspiration rates make difficult to perform a comparative analysis
 626 because of the different units of measurement used by authors, Table 7 shows all data summarized and
 627 converted into kg/m^2 to facilitate the cross-comparison of the findings.

628 *Table 7. Summary of the minimum and maximum values obtained from the parameters reviewed in experimental studies*

Reference	Parameter	Description	Minimum value	Maximum value	Units	Climatic conditions	Minimum value $\text{kg m}^{-2} \text{ day}^{-1}$	Maximum value $\text{kg m}^{-2} \text{ day}^{-1}$
[49]	Sky conditions	Sunny day+wet soil	-	9.3	mm	Hong Kong (Cwa)	-	9.3
		Sunny day+moist soil	-	9.0			-	9.0
	Sunny day+dry soil	-	13.1	-			13.1	
	Moisture soil	Cloudy day+wet soil	-	8.1			-	8.1
		Cloudy day+moist soil	-	5.0			-	5.0

		Cloudy day+dry soil	-	5.8		-	5.8			
[69]	Season	August	-	0.08	g m^{-2} s^{-1}	Kobe (Cfa)	-	6.9		
	Vegetation	November	-	0.02			-	1.72		
		Bare soil	-	0.05			-	4.3		
		Soil UVA. Solar radiation simulated with UVA lamps for the experiment with a green roof sample without plants.	30	130			1.1	4.6		
		Soil Day. Solar radiation simulated with Fluorescent Daylighting VHO lamps for the experiment with green roof sample without plants.	40	100			1.4	3.6		
		UVA plants. Solar radiation simulated with UVA lamps for the experiment with a green roof sample with <i>S. spurium</i>	95	115			3.3	4.0		
[46,54]	Solar radiation Relative humidity Wind speed Air temperature	Base. Solar radiation simulated with Fluorescent Daylighting VHO lamps for the experiment with green roof sample with <i>Delosperma nubigenum</i> .			W m^{-2}	Pennsylvania (Dfb)				
		Humidity. Conditions equal to 'Base' experiment, except that relative humidity was set to 50%.	50	140					1.8	4.9
		Solar. Conditions equal to 'Base' experiment, except solar radiation decreased by 50%.	25	55					0.9	1.9
		Wind. Conditions equal to 'Base' experiment, except wind speed increased to 1 m/s.	40	170					1.4	6.0
		Temperature. Conditions equal to	60	140					2.1	4.9

‘Base’ experiment,
except air temperature
changed to 26 °C.

Base II. Conditions equal
to ‘Base’ experiment in
order to duplicate the
measurements.

			40	150			1.4	5.3
[55]	Vegetation	Sedum	-	5.0		La Rochelle	-	5.0
		Grass	-	8.0	mm	(Cfb)	-	8.0
		Bare soil	-	4.2			-	4.2
[48]	Vegetation	Sedum	20	210		Melbourne	0.7	7.4
		Bare soil	20	280	W m ⁻²	(Cfb)	0.7	9.9
[56]	Vegetation	Soil moist	4.0	6.0			4.0	6.0
		Pennisetum	7.0	9.0			7.0	9.0
		Aptenia	3.0	6.0	L m ⁻² day ⁻¹	Tel Aviv (Csa)	3.0	6.0
		Sesuvium	6.5	7.5			6.5	7.5
		Halimione	7.5	4.0			7.5	4.0
[57]	Vegetation	Periwinkle	0.5	5.0		La Rochelle	0.5	5.0
		Grass	0.5	3.5	kg m ⁻² day ⁻¹	(Cfb)	0.5	3.5
		Soil bare	0.5	3.0			0.5	3.0
[58]	Substrate	Normal soil	2.0	6.0			2.0	6.0
		Artificial soil	2.0	6.0	kg m ⁻² day ⁻¹	Singapore (Af)	2.0	6.0
		Artificial soil + water retention	4.0	7.0			4.0	7.0

629

630 The variability of the results depends on both the instrumentation and the parameters (plant species, substrate
631 type, climatic conditions, etc.) influencing the ET process.

632 In terms of weight, the ET maximum values were 7.0 kg m⁻² day⁻¹ and 3.0 kg m⁻² day⁻¹ respectively, using
633 artificial soil with water retention layer below the substrate and bare soil. In terms of water lost by
634 evapotranspiration, the maximum values during a sunny day were 13.1 mm with dry soil and 8.0 mm using
635 grass. Latent heat flux reached the maximum value with high wind speed conditions (170 W m⁻²) and using
636 bare soil (280 W m⁻²) compared to *Sedum* (210 W m⁻²).

637 Most of the analysed studies performed a comparison between green roof evapotranspiration (plants +
638 substrate) and bare soil evaporation (only substrate). However, few of them evaluated ET when different
639 solutions of green roof layer were alternated and compared, and/or varying the plant species [55–57].
640 Moreover, only Tan et al. (2017) [58] measured evapotranspiration rates varying the substrate type.

641 Few studies evaluated the evapotranspiration under different environmental boundary conditions. In
642 particular, in [49], the weather was differentiated into three types: sunny, cloudy and rainy. Interestingly, Jim
643 and Peng (2012) [49] claim that the dry soil reached $13.1 \text{ kg m}^{-2} \text{ day}^{-1}$ and the wet soil $9.3 \text{ kg m}^{-2} \text{ day}^{-1}$
644 during sunny days. This assumption underlines the importance in evaluating, not only the substrate water
645 content, but also the climatic conditions. Because the limited substrate-moisture effect on ET and associated
646 cooling that could be explained due to sufficient water supply by occasional rainfall events and regular
647 irrigation confined soil moisture variations to a small range during the summer period and to the relatively
648 weak capability of the substrate to hold water tightly during the dry state to resist ET water extraction.
649 This survey has highlighted a lack of studies concerning the effect of the drainage layer on ET. This could be
650 an interesting field for future studies considering that the drainage layer is particularly important since it has
651 the aim of ensuring an optimal balance between air and water within green roof system.
652 Further researches also should focus on optimizing green roof technology with a water retention layer inside
653 the drainage layer in order to increase ET.

654

655 **6. Mathematical models to characterize ET on green roofs**

656 *6.1. Heat and mass transfer models for ET in green roofs*

657 Due to the heat and mass transfer through the roof resulting from shading, insulation, cooling
658 (evapotranspiration) and wind effects, modelling the latent heat flux of green roofs is not a simple process.
659 Many researchers have explored the heat exchange between green roofs and the environment in which the
660 heat and mass transfer in soil were mostly taken as a quasi-steady-state process.

661 The energy exchanged between the green roof surface and the outside environment consists of latent and/or
662 sensible heat. Latent heat is the heat loss by evapotranspiration that involves soil surface evaporation and
663 vegetation transpiration. Evapotranspiration affects the net heat flux by modulating incoming/outgoing heat
664 transfer mechanisms, depending on the plant species and on environmental conditions. An increase in the
665 evapotranspiration rate decreases the convection heat flux related to sensible heat and storage [61]. Several
666 studies obtained numerical results of each heat flux in order to quantify the latent heat flux.

667 Most of the studies used the following equations to evaluate latent heat flux on the plant canopy (L_F) and the

668 soil surface (L_G) [91]:

$$669 \quad L_F = LAI \frac{\rho_{af} c_{pa}}{\gamma(r_a + r_{sto})} (q_c - q_{af}) \quad (2)$$

$$670 \quad L_G = \frac{\rho_{af} c_{pa}}{\gamma(r_g + r_a)} (q_g - q_{af}) \quad (3)$$

671 Stomatal resistance for transpiration r_{sto} is influenced by factors including solar radiation and vapour pressure
 672 difference, volume water content, temperature of soil. Air resistance for transpiration r_a is associated with
 673 plant height and wind speed [92].

674 The evapotranspiration rate from plant canopy and soil surface can be calculated by the following equations:

$$675 \quad E_c = L_c / \mu \quad (4)$$

$$676 \quad E_g = L_g / \mu \quad (5)$$

677 Feng et al. (2010) [52] simplified heat losses by transpiration (L_c) and evaporation (L_g) in one equation, so
 678 the heat loss by evapotranspiration is given by:

$$679 \quad L_{et} = L_c + L_g = E_{et} \mu \quad (6)$$

680 where, E_{et} is the evapotranspiration rate and is given by $E_{et} = E_c + E_g$. Evapotranspiration rates can be
 681 measured by weighing or by using soil hygrometers, as explained above. This approach was used by
 682 Quezada-Garcia et al. (2017) [93] to develop a heterogeneous model of heat transfer for green roofs.

683 Table 8 summarizes all the references regarding the ET phenomenon within green roofs studies. This table
 684 reports that a heat transfer model for green roofs is based on different approaches and equations to evaluate
 685 the required parameters for the calculation of latent heat flux.

686 *Table 8. Equations and/or models adopted in heat transfer models for green roofs and their validation parameters*

References	Previous equation utilized	Input parameters	Validation parameters
[70]	-	Meteorological data Substrate temperature	Temperature at 2 cm below soil Degree of saturation in substrate
[50]	Rana-Katerji [94]	-	-
[46]	-	Air temperature Air relative humidity Air speed Sky temperature Incoming solar radiation Substrate water content LAI	Evapotranspiration Incident incoming short-wave radiation Incident incoming long-wave radiation Outgoing long-wave radiation Heat fluxes through green roofs Convective heat transfer fluxes Substrate top and bottom layer temperatures

		Substrate temperature	Substrate thermal conductivity Plant temperatures Average substrate volumetric water contents Air velocities Room air relative humidity levels and temperatures Spectral reflectivity of green roof samples Leaf Area Index (LAI)
[93]	Feng et al. [52]	-	Green layer temperature
		Weather data Characteristics of vegetation Characteristics of soil	Soil surface temperature Temperature at 2 - 8 cm below soil
[60]	Banna [95]	-	-
[61]	Levallius [96]	-	-
		Weather data Characteristics of vegetation Characteristics of soil	Soil surface temperature
[62]	Deardoff [97]	-	-
		Height of plant Minimum stomata resistance Average LAI Soil thermal capacity Soil depth Soil conductivity Reflectivity of leaves Soil water conductivity Soil water capacity	Temperature Moist distribution Heat flux
[76]	Choudhury and Monteith [98] Philip and De Vries [99]	-	-

687

688 Most of the developed mathematical models that analyse the energy performance of green roofs were then
689 validated through experimental analysis. Table 8 also shows the principal parameters used to validate the
690 green roof models.

691 Unlike the models presented in section 2, which were developed to evaluate evapotranspiration on bare
692 and/or vegetated soils, the models listed in Table 8 concern green roofs were developed to analyse the energy
693 performance of green roofs. They considered latent heat and not having the ultimate aim of evaluating the
694 phenomenon of evapotranspiration.

695 Among all the models, only Tabares-Velasco and Srebric (2012) [46] measured evapotranspiration in a
696 laboratory set-up to validate the model. Most of the models used soil and/or plant temperatures measured in-

697 situ to validate the proposed models.

698 Some studies, around 35% of the literature reviewed, adopted simplified energy balance models because of
699 the complex structures of green roofs that include canopy and soil. In particular, Tian et al. (2017) [59]
700 analysed the loss of water in the soil through evapotranspiration considering that it occurred only on the
701 surface of soil while He et al. (2016) [53] assumed that the change of soil water content is equal to water loss
702 through evapotranspiration.

703 Hodo-Abalo et al. (2012) [60] developed a model for evaluating the cooling potential of green roofs. The
704 authors solved the heat transfer equations using a finite difference scheme and Thomas algorithm. The
705 authors developed a numerical model based on an implicit finite difference method for discretizing time-
706 average Navier-Stokes equations and for calculating evapotranspiration variations. Evapotranspiration was
707 obtained by summing the hourly values of local latent heat flux from different layers within the canopy,
708 added to the hourly value of soil evaporation.

709 Djedjig et al. (2012) [70] developed a thermo-hydric model considering the thermal inertia of the whole
710 green roof system. This model allowed an explicit calculation of the evapotranspiration, and the thermo-
711 physical properties of the substrate were calculated according to the volumetric water content. The results
712 demonstrate the effectiveness of the explicit calculation of evapotranspiration, unlike the Penman–Monteith
713 equation, which does not incorporate water stress.

714 Tabares-Velasco and Srebric (2012) [46] included a complete validation of heat transfer fluxes, such as
715 evapotranspiration rates. The study had laboratory-rated acquisition equipment for the detailed measurement
716 of evapotranspiration rates by the gravimetric method, while simultaneously measuring the total energy
717 balance on the green roof sample. Thus, the authors used the experimental data to calibrate the green roof
718 evapotranspiration model.

719 The study conducted by Tsang and Jim (2011) [61] modelled a quadratic-like relation between
720 evapotranspiration and the water content in green roofs that allowed an analysis of the latent heat flux of
721 green roofs in terms of volumetric water content in the soil and the relative humidity. This model considers
722 the combined effect of evaporation and transpiration to reduce calculation complexities.

723 He et al. (2017) [76] analysed energy balance of plant and soil layer using a coupled hydro-thermal transfer
724 model validated by field experiments in Shanghai area. In particular, the authors assessed the effects of

725 thickness of soil layer and leaf area index of plant layer on green roof energy and thermal performance. In
726 the model, it was assumed that the water content variation of soil layer equals to the water loss
727 through evapotranspiration.

728 All heat transfer models of green roofs take into account the latent heat flux due to evaporation of water from
729 the substrate and transpiration of plants. However, only a few of them considered experimental data for their
730 validation. Future models should include experimental measurements of ET rates for the validation process.

731 6.2. Latent heat flux results

732 This section describes the results found by the studies that used mathematical models to characterize ET on
733 green roofs in order to evaluate the surface energy, focussing on the latent heat flux.

734 Evapotranspiration and net long wave radiation dominate the energy balance of the green roof. In particular,
735 He et al. (2016) [53] found that, under both free-floating and air-conditioned scenarios, the
736 evapotranspiration flux accounted for 58.15% and 63.93% respectively of all the dissipated heat by the green
737 roof. When the moisture content of the soil is low, the proportion of evapotranspiration decreases greatly
738 while heat convection rises. Similar results were obtained by Feng et al. (2010) [52], who found that the heat
739 loss through the evapotranspiration of the plants–soil system accounted for 58.4% of the total energy flux
740 and played the most important role. The net long-wave radiative exchange between the canopy and the
741 atmosphere as sensible heat accounts for 30.9%, and the net photosynthesis of plants accounts for 9.5%.
742 Only 1.2% was stored by plants and soil, or transferred into the room beneath. During the day, Tian et al.
743 (2017) [59] found that most of the absorbed radiation (about 40%) is dissipated as latent heat on the canopy.
744 However, other studies found controversial results regarding the role of evapotranspiration in the green roof
745 energy balance. Schweitzer and Erell (2014) [56] estimated that the contribution of evaporation was the least
746 important of these mechanisms (about 4%). In addition, Coutts et al. (2013) [48], through an experimental
747 analysis, evaluated the surface energy balance for green roof and bare soil, showing that only a small portion
748 of the overall heat flux was partitioned into latent heat (0.15%) for green roof and for bare soil (0.13%).
749 These results show that when succulent vegetation with coverage less than 100% and in absence of irrigation
750 the evapotranspiration achieves modest benefits. The mean daytime evaporative fraction is strictly connected
751 with the time of irrigation. It increased about 41% for green roof and 51% for bare soil immediately after the

752 irrigation, while by the third day of having watered the latent heat flux was reduced by 26% in the green roof
 753 and by 38 % in the bare soil.

754 The study conducted by Lazzarin et al. in 2005 [50] evaluated the performance of a green roof system in
 755 summer in both dry and wet conditions. The wet soil gave rise to an evapotranspiration rate of about 25.0%
 756 of the overall heat flux, whereas in dry conditions that contribution was limited to 12.0%.

757 Tsang and Jim (2011) [61] observed that the peaks of latent heat flux (about 7 Wm^{-2}) were achieved when
 758 long period of high solar radiation occurred. Thus, solar radiation could expedite the evapotranspiration rate
 759 and increase the latent heat loss.

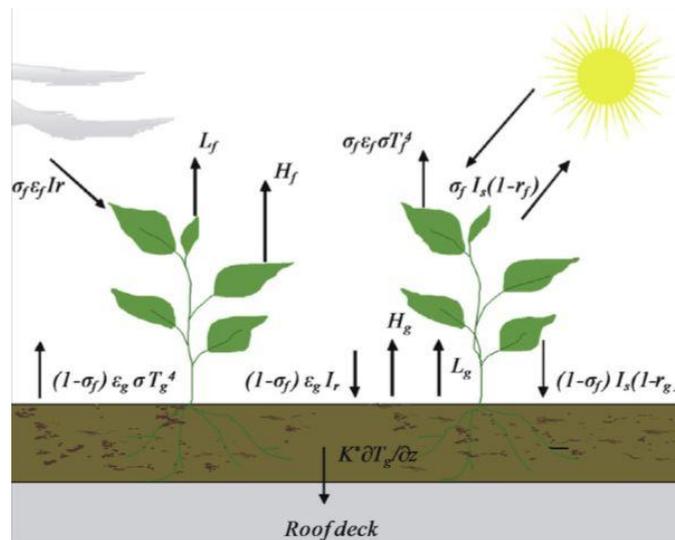
760 These results show the importance of evapotranspiration in reducing thermal loads in a green roof. As a
 761 general outcome of this section, it is possible to observe that the latent heat flux calculated through
 762 mathematical models showed a wide range of values on the overall heat flux in a green roof, depending on
 763 the mathematical model used and the boundary conditions assumed (climatic conditions).

764

765 7. Evaluation of ET through dynamic simulation

766 7.1. EnergyPlus software

767 This section shows the ET results obtained by using EnergyPlus [63–65] dynamic simulation software.



768

769

Figure 5. Energy balance of a green roof [17]

770 EnergyPlus integrates a green roof model developed by Sailor (2008) [100] and based on an Army Corps of
 771 Engineers' FASST vegetation model [101]. This model considers simultaneously the foliage surface and soil

772 temperatures at each time step. The “Ecoroof” module is a one-dimensional model containing energy
 773 budgets for both the foliage layer and the soil surface. It considers long and short wavelength radiation
 774 exchanges, the effects of vegetation on convective (sensible heat) thermal flux, evapotranspiration (latent
 775 heat), heat storage and transfer through the substrate (Figure 5).

776 The energy balance for the foliage is the following (Eq. 1):

$$777 \quad F_f = \sigma_f [I_s(1 - \alpha_f) + \varepsilon_f I_{ir} - \varepsilon_f \sigma T_f^4] + \frac{\sigma_f \varepsilon_f \varepsilon_g \sigma}{\varepsilon_1} (T_g^4 - T_f^4) + H_f + L_f \quad (9)$$

778 where $[I_s(1 - \alpha_f) + \varepsilon_f \sigma T_f^4]$, $\frac{\sigma_f \varepsilon_f \varepsilon_g \sigma}{\varepsilon_1} (T_g^4 - T_f^4)$, H_f and L_f are shortwave solar radiation, long wave
 779 radiation exchange between sky and foliage, convective heat transfer between air and foliage as sensible heat
 780 flux, and evapotranspiration on the foliage surface as latent heat flux, respectively.

781 The energy balance for the soil surface is the following (Eq. 2):

$$782 \quad F_g = (1 - \sigma_f) [I_s(1 - \alpha_g) + \varepsilon_g I_{ir} - \varepsilon_g T_g^4] - \frac{\sigma_f \varepsilon_f \varepsilon_g \sigma}{\varepsilon_1} (T_g^4 - T_f^4) + H_g + L_g + k \times \frac{\delta T_g}{\delta z} \quad (10)$$

783 where all the terms have the same meaning as in Equation (1), but are referred to the soil layer. The last term
 784 represents the conductive heat transfer in the soil substrate.

785 The “Ecoroof” module allows to specify various features of the green roof, including height of plants, leaf
 786 area index (LAI), leaf reflectivity, thickness/density/thermal conductivity and specific heat of soil.

787 Table 9 provides **input** data for the green roof model in EnergyPlus reported by Peri et al. (2016) [79].

788 However, many previous studies assuming theoretical data for the features of substrate and plant species
 789 have already been developed. Therefore, the thermo-physical values used in the simulations not always may
 790 be confirmed through experimental test. As rule, it is necessary to use only realistic thermo-physical values,
 791 which have to be associated with specific plant and substrate types.

792 *Table 9 Range of values provided by Peri et al. (2016) [79] for an EnergyPlus model*

Input Parameter	Range of values	
	Minimum	Maximum
LAI	0.1	5
σ_f	0	1
Canopy albedo	0.1	0.4
ρ_g	0.04	0.4
k_l	0.3	0.83
σ_t	0.11	0.5
τ_t	0.2	0.2

793 *7.2. ET results using EnergyPlus*

794 Boafo et al. (2017) [63] investigated the potential contribution of the evapotranspiration in green roofs on the
795 annual energy consumption of an office building located in Incheon, Republic of Korea. So this study could
796 be representative of the Dwa climate according with the Köppen classification (2006) [102]. The
797 evapotranspiration flux was evaluated varying the LAI (from 1 to 5) as well the irrigation regime. They
798 found that the average monthly **evapotranspiration** ranged from 1.80 mm·day⁻¹ to 4.79 mm·day⁻¹ for high
799 LAI, from 0.31 mm·day⁻¹ to 4.16 mm·day⁻¹ for low LAI from 1.31 mm·day⁻¹ to 4.28 mm·day⁻¹ for high
800 irrigation. For the scenarios without irrigation the ET varied from 1.31 mm · day⁻¹ to 3.92 ·mm day⁻¹, in
801 December and May respectively. As expected, the highest and lowest evapotranspiration fluxes were found
802 during summer and winter, respectively. The latent heat flux, associated to the evapotranspiration, increasing
803 the LAI from 1.0 to 5.0, was grown-up by 10.4% in summer and 80.2% in winter keeping soil thickness
804 constant. Silva et al. (2016) [64] analysed the thermal performance of intensive and extensive green roofs
805 located in Lisbon, Csa climate according to the Köoppen classification. The evapotranspiration was
806 significantly different in extensive green roofs (max value 2 mm·day⁻¹·10⁻⁴) when compared to semi-
807 intensive (max value 6 mm·day⁻¹·10⁻⁴) and intensive roofs (max value 9 mm·day⁻¹·10⁻⁴), particularly in
808 summer when the solar radiation was higher. Vera et al. (2017) [65] investigated the effect of the variation of
809 the LAI of the green applied over an uninsulated concrete slab and lightweight metal roofs, in different
810 climate, i.e. Bsk (Albuquerque), Csc (Santiago) and Cfb (Melbourne) according to the Köppen classification.
811 In this study, the LAI values were varied between 0.1 and 5.0 that represent the range of potential values for
812 vegetated roofs. The results show that the cooling load of the room decreases when LAI increases because of
813 the increase in the evapotranspiration that diverts incoming solar heat gains through the roof, for the three
814 evaluated cities. A heat flux reduction of about 20.0 W/m² was calculated when a vegetated roof without
815 plant was compared to a vegetated roof with plants having a LAI equal to 5.0. Finally, the highest
816 evapotranspiration flux was achieved with a LAI of 4.79 mm·day⁻¹) and irrigation of 4.28 mm·day⁻¹ during
817 the summer period.

818

819 **8. Sensitivity analysis of green roof ET**

820 The above performed review have highlighted that there is a plethora of parameters, as well as their
821 reciprocal meddling, that affect the evapotranspiration process. Thereby, several studies from the literature
822 review have tried to perform sensitivity analysis to understand which parameter most affects ET.

823 Tsang and Jim (2011) [61] have investigated the influence of the volumetric water content and the air
824 convection coefficient on the performance of the green roofs. Their sensitivity test showed that an increase
825 from 30 to 60 % of VWC implies a reduction of heat stored in the green roofs by 24 %. While, the increase
826 from 12 to 16 $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ of the convection coefficient reduces the heat stored by 45 %.

827 Tabares-Velasco and Srebric (2012) [46] carried out a sensitivity analysis of the energy performance of the
828 green roof, considering the effect of soil thickness, wind velocity, volumetric water content, solar radiation,
829 and stomatal resistance. The results of this study provide, in function of the parameters and their range of
830 variation analysed, the evapotranspiration rate expressed as latent heat flux. Starting from these results,
831 Figure 6 has been developed in this review study with the aim to synthetize and systemize the reading of the
832 performed study by Tabares-Velasco and Srebric (2012).

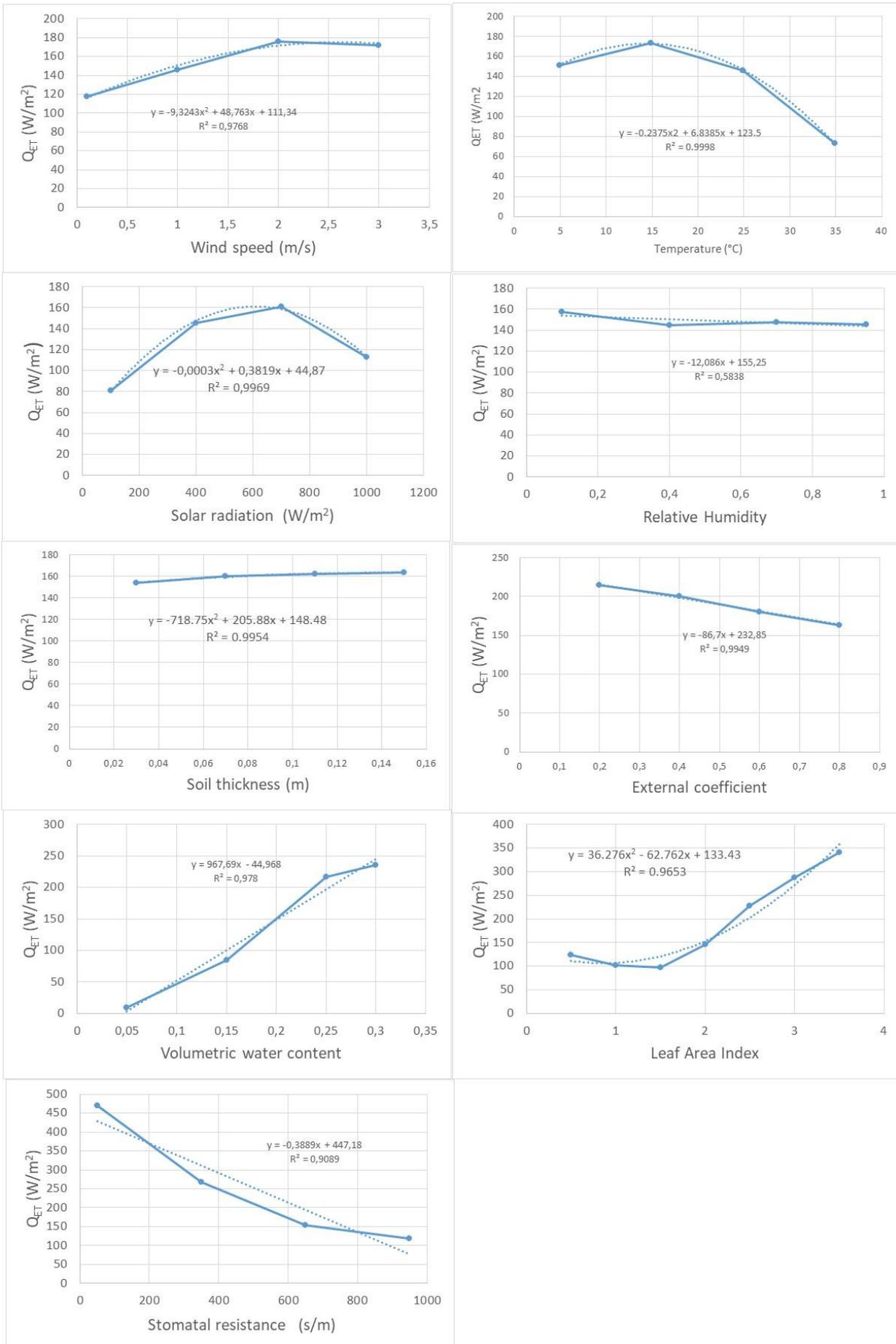


Figure 6. ET Sensitivity analyses

835 This sensitivity analysis highlighted that the highest values of evapotranspiration were obtained with high
836 volumetric water content in the substrate (0.25 and 0.30), reduced stomatal resistance (50 and 350 s/m), high
837 values of LAI (2.5, 3.0 and 3.5), and with low values of external coefficient, i.e. incoming long and short
838 wave radiation, (0.2 and 0.4). **Where the radiation emitted from earth/atmosphere is terrestrial or longwave
839 radiation and the radiation emitted from sun is solar or shortwave radiation.** These results can be inferred by
840 observing the value assumed for the different percentage between the minimum and maximum values of ET
841 (ΔQ_{ET}). The volumetric water content is the variable with the largest difference ($\Delta Q_{ET}=96.3\%$) between the
842 minimum and maximum value of evapotranspiration, from 8.8 to 235 W/m^2 .
843 Stomatal resistance and LAI also produce considerable variations in the ET, with values between 469.5 and
844 118.5 W/m^2 ($\Delta Q_{ET}=74.8\%$) and between 340.6 and 97.4 W/m^2 , ($\Delta Q_{ET}=71.4\%$), respectively.
845 In a similar manner, the variables with less influence on evapotranspiration process were identified. When
846 substrate thickness and relative humidity vary, the evapotranspiration flux remains almost constant, with a
847 ΔQ_{ET} variation of 5.8 and 7.8 %, respectively. Values of evapotranspiration lower than 145 $W \cdot m^{-2}$ are never
848 reached whatever was the variations in relative humidity, substrate thickness, and long and short wave
849 radiation.
850 Furthermore, Figure 6 shows that wind speed, volumetric water content, and leaf area index have a positive
851 correlation with ET, i.e. the higher these values, the higher the ET. Otherwise, air temperature, external
852 coefficients (long and short wave radiation), and stomatal resistance are characterized by a negative
853 correlation with ET. Finally, relative humidity and soil thickness present a neutral correlation.
854 The performed elaboration allows to evidence as all the parameter variations can be represented by means of
855 a second order polynomial regression, which shows rather high value of the correlation coefficient R^2 .
856 Therefore, this correlation could constitute a reference for comparing set of experimental results coming
857 from different studies.
858 Moreover, a frequency analysis on the results coming from Tabares-Velasco and Srebric (2012) [62] was
859 also carried out. It is possible to observe that the highest frequencies of Q_{ET} are in the range 100-149 and
860 150-199 Wm^{-2} (Figure 7, left). The cumulative curve (Figure 7, right) indicates that 90% of the values of Q_{ET}
861 are lower than 249 Wm^{-2} .

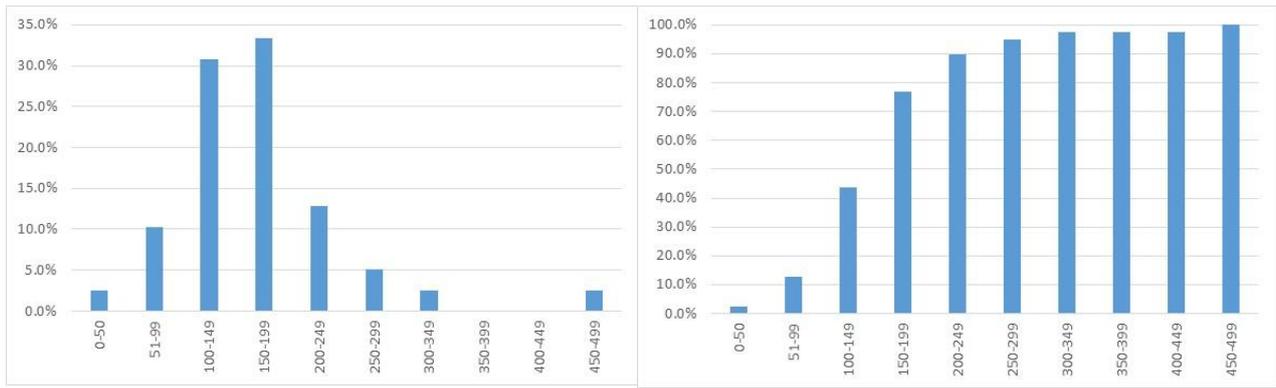


Figure 7. A frequency analysis of energy for evapotranspiration Q_{ET} (left) and the cumulative curve (right)

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This section has highlighted which factors are influencing ET and how their variation has positively or negatively affect evapotranspiration. Moreover, after having analysed data from the literature the correlations, as well as the range of variation of ET found, helps in establishing a comparative framework between different researches.

9. Conclusions

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The purpose of this study was to review the impact of ET on green roofs. Although most of the studies agree to consider evapotranspiration among the main factors affecting the behaviour of green roofs, only few studies experimentally assessed evapotranspiration rates. The following general conclusions can be drawn:

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- The experimental studies carried out have made use a wide variety of equipment and techniques for the measurement of ET. When the objective is directly to assess the evapotranspiration of green roofs, high precision load cells that determine the evolution of weight over time are the most widely used equipment.

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- Many of the mathematical models used to evaluate the performance of green roofs take into account the latent heat flux due to evaporation of water from the substrate and transpiration of plants. However, only few models were validated considering experimental data of evapotranspiration rates, and in many cases, the experiments were conducted in laboratory conditions and for short periods. Therefore, more research that experimentally analyses all factors that affect the ET phenomenon under real conditions will help to fill the gap in the current state of the art.

883

884

- The high variability of technical-constructive solutions and climatic conditions affecting the energy performance of green roofs, the different units of measurement used to quantify evapotranspiration,

885 the lack of information regarding the duration of the experiments, and the specific climatic
886 conditions make it difficult to compare the results obtained from different studies. Thus, some
887 guidelines to develop a correct experimental methodology could help in providing better
888 comparative analysis for future research.

- 889 - Some studies evaluated evapotranspiration in green roofs by comparing roofs with and without
890 vegetation and by implementing different plant species. However, only few of them evaluated the
891 evapotranspiration rate by varying the type of substrate. Finally, an important lack of studies
892 considering the role of the drainage layer in the ET process of a green roof was also detected.
- 893 - There are geographic areas of the world with high potential ET rates where this phenomenon has not
894 yet sufficiently evaluated for green roofs.
- 895 - There are no studies correlating ET with external surface temperatures of the green roof, although
896 many studies determined that one of the main advantages of using green roofs is the reduction of
897 surface temperatures and the consequent mitigation of the urban heat island effect.

898 Furthermore, the following are the specific conclusions:

- 899 - Load cells are the equipment that could be recommended for future studies to assess the
900 evapotranspiration of green roofs in a direct and high precision way. They allow monitoring the
901 evolution of the tray weights due to water loss over time in $\text{kg m}^{-2} \text{day}^{-1}$ that is the most appropriate
902 unit of measurements to estimate the evapotranspiration at any desired time-step.
- 903 - The sensitivity analysis highlighted that the highest values of evapotranspiration were achieved with
904 high volumetric water content in the substrate, reduced stomatal resistance and high values of LAI.
- 905 - On one hand, the variation of the volumetric water content in the substrate causes the largest
906 fluctuation between the minimum and maximum values of evapotranspiration. On the other hand,
907 the variation in the substrate thickness and relative humidity showed the minimum variation on the
908 heat flux, being the parameters that less affect the ET in a green roof.
- 909 - Here the importance of testing experimentally the ET process during enough extended periods of
910 time, covering all the different seasons and climate conditions to correlate the ET with the main
911 meteorological scenarios (e.g. sunny, cloudy, and rainy days) have to be highlighted.

912 - Moreover, further studies should be carried out to assess the evapotranspiration of different green
913 roof solutions considering the influence of the drainage, as well as to investigate those geographic
914 areas of the world, which has high potential for green roof evapotranspiration.

915 Globally, this review analysis provides valuable information for building companies, architects, engineers,
916 designers and stakeholders, on the ET of various green roof solutions and the different materials used. In
917 addition, this paper highlighted the principal gaps in the current literature that will lead researchers to
918 perform new studies within this topic.

919

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928

929 **Nomenclature**

930	C_d	Denominator constant that changes with reference type and calculation time step, s/m
931	C_n	Numerator constant that changes with reference type and calculation time step, $K \text{ mm s}^3 \text{ M/g/d}$ or K
932		$\text{mm s}^3 \text{ M/g/h}$
933	C_{pa}	Specific heat of air at constant pressure, $\text{J/kg}^\circ\text{C}$
934	e_a	Actual vapour pressure, kPa
935	e_s	Saturation vapour pressure
936	E_g	Evaporation rate on soil surface, $\text{kg/m}^2/\text{s}$
937	E_c	Transpiration rate on plant canopy, $\text{kg/m}^2/\text{s}$
938	E_{et}	Evapotranspiration rate, $\text{kg/m}^2/\text{s}$
939	ET	Evapotranspiration rate, mm/h
940	ET_0	Reference evapotranspiration rate from a grass surface, mm/h
941	ET_{sz}	Reference evapotranspiration rate from a standardized surface, mm/h
942	F	Net heat flux, W/m^2
943	G	Soil heat flux, W/m^2
944	H	Sensible heat flux, W/m^2
945	K	Dry soil thermal conductivity W/m/K
946	I_{ir}	Total incoming long wave radiation, W/m^2
947	I_s	Total incoming short wave radiation, W/m^2
948	L	Latent heat flux, W/m^2
949	L_c	Latent heat flux on plant canopy, W/m^2
950	L_g	Latent heat flux on soil surface, W/m^2
951	L_{et}	Latent heat flux from evapotranspiration, W/m^2
952	LAI	Leaf area index, -
953	PET	Potential ET rate, mm/h
954	q_{af}	Vapour pressure of the air within plant canopy, Pa
955	q_c	Vapour pressure of the air in contact with plants, Pa
956	q_g	Vapour pressure of the air in contact with soil, Pa

957	Q_{ad}	Energy transported by evapotranspired water, W/m^2
958	Q_a	Sensible heat flux to the air, W/m^2
959	Q_s	Heat flux to the soil, W/m^2
960	Q_c	Heat storage in the crop, W/m^2
961	Q_p	Energy available for photosynthesis, W/m^2
962	R_n	Net solar irradiance, W/m^2
963	R_s	Incoming solar irradiation, $MJ/m^2/d$ or $MJ/m^2/h$
964	r_a	Aerodynamic resistance to transpiration, s/m
965	r_{sto}	Stomatal resistance to vapour diffusion, s/m
966	r_g	Aerodynamic resistance to evaporation on soil surface, s/m
967	T	Temperature, K
968	T_a	Mean monthly/daily/hourly air temperature, $^{\circ}C$
969	TD	Mean maximum minus mean minimum temperature, $^{\circ}C/day$
970	T_F	Mean monthly/daily/hourly air temperature, $^{\circ}F$
971	u_2	Wind speed at 2m height, m/s
972	z	Height or depth, m
973	<i>Greek letters</i>	
974	α	Albedo, -
975	Δ	Slope of saturation vapour pressure with air temperature, $kPa/^{\circ}C$
976	ε	Thermal emissivity, -
977	ε_1	View factor, -
978	γ	Thermodynamic psychometric constant, kPa/K
979	ρ_a	Air density, kg/m^3
980	ρ_{af}	Density of air within plant canopy, kg/m^3
981	λ	Latent heat of evaporation, MJ/kg
982	μ	Latent heat of vaporization of water, J/kg
983	σ	Stefan-Boltzmann constant, $W m^{-2} K^{-4}$
984	σ_f	Fractional vegetation coverage, -

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The evapotranspiration process in green roofs: a review

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Abstract

Previous research has shown that most of the green roof benefits are related to the cooling effect. In the literature available, however, it is still not clear how and how much the evapotranspiration affects the performance of a green roof. In order to fill the gap in this research topic, this study carries out a review on the cooling effect due to the evapotranspiration process of green roofs. First of all, an overview of the evapotranspiration phenomenon in green roofs, as well as the equipment and methods used for its measurement are presented. Then, the main experimental results available in literature, the physical-mathematical models and the dynamic simulation software used for the evaluation of the latent heat flux are also analysed and discussed among the available literature. Moreover, this review proposes a classification of the results carried out by previous studies as function of the main parameters affecting the evapotranspiration process (e.g. volumetric water content, stomatal resistance, Leaf Area Index, solar radiation, wind velocity, relative humidity, soil thickness, and substrate composition). Additionally, a sensitivity analysis of the results obtained from the literature allowed underlining the correlation among the main factors affecting the evapotranspiration. Finally, a vision of the world area where green roof studies were performed is provided. From the results, it is possible to emphasize that most of the studies that evaluated the evapotranspiration used high precision load cells. Furthermore, all the heat transfer models of green roofs considered in this review took into account the latent heat flux due to evaporation of water from the substrate and plants transpiration, however, only few of them were experimentally validated.

Keywords: evaporation; transpiration; latent heat flux; cooling effect;

29 **1. Introduction**

30 In recent years, the continued growth of high-density urban areas, characterized by extensive paved areas,
31 have increased the overwarming and energy needs within the cities [1,2]. Furthermore, these areas often have
32 higher air temperatures than their rural surroundings which is commonly called urban heat island (UHI)
33 effect [3,4]. Engineers, researchers, and designers are committed to develop sustainable solutions to reduce
34 both energy consumption and pollutant emissions by using innovative materials and technologies [5,6]. One
35 of the most effective solutions adopted in the field of bioclimatic architecture is the replacement of materials
36 traditionally used in flat roofs, which comprise around 25% of the total horizontal surfaces in urban areas,
37 with green roof technologies [7].

38 Green roofs provide several benefits at both building and city level. The following are the most commonly
39 observed at urban scale: mitigation of urban heat island effect [8–10]; decrease in storm water runoff [11,12];
40 enhancement of biodiversity in densely urban areas [13]; purification of air and water runoff [14]. At
41 building scale, green roofs reduce the sensible heat flux due to the cooling effect [15,16] thus decreasing the
42 heating and cooling demand of a building [17–19], and improving human thermal comfort [20,21]. This
43 effect may vary depending on the climate conditions [22–24], and the level of insulation specially in cases of
44 building retrofitting [25,26]. Most of these multiple benefits are linked to the cooling effect due to the
45 evapotranspiration process (ET) that humidifies the external ambient air, reduces the surface temperature of
46 the roof [27], and mitigates the urban heat island phenomenon [28].

47 Previous studies have considered the cooling effect due to the evapotranspiration process among the major
48 energy benefits of green roofs [29,30]. The importance of evapotranspiration in energy transfer models was
49 also highlighted in previous studies [31] in which the authors analysed the vegetation effect on horizontal
50 surfaces in urban, suburban and agricultural environments. However, the existent literature is scarce and
51 controversial in evaluating the physical-mathematical models and dynamic simulation software for
52 calculating ET, the main influencing parameters that have to be considered, and the suitable equipment and
53 methodologies for the measurement in urban contexts.

54 To fill these gaps in the literature, the present study carried out a wide analysis of the cooling effect due to
55 the evapotranspiration process on green roofs. The scope of this paper includes the analysis and discussion of
56 the following topics: the main equipment and methodologies used to measure the ET in green roofs, the

57 correlation between evapotranspiration and the energy performance of green roofs, the main experimental
58 results from the literature and the physical-mathematical models used to calculate the latent heat flux on
59 green roofs. Furthermore, this paper provides an exhaustive review of the main influencing parameters of ET
60 in green roofs and their classification according to the potential evapotranspiration capacity.

61 However, due to the high number of studies carried out on green roofs, this review is focused on the research
62 that expressly evaluate experimentally or analytically the evapotranspiration process in green roofs.
63 Therefore, all researches examining performance and benefits of green roofs without directly correlating
64 them with evapotranspiration is out of the scope of this study. In addition, the previous studies that have
65 evaluated the role of evapotranspiration in the hydraulic performance and water balance of green roofs, in
66 terms of storm water management and runoff of these systems, are not included in this review.

67 In order to organize the reviewed data and to facilitate the understanding thereof, paper is structured in seven
68 sections as follows: Section 2 provides a general description of evapotranspiration process, how it is defined,
69 what does it depends on and how it can be determined. Section 3 and 4 show the main climatological
70 parameters and characteristics of vegetation and substrate that influence the ET of green roofs, respectively.
71 Section 5 describes the principal experimental measurement methods used to evaluate the evapotranspiration
72 of green roofs, the results obtained from them and a summary of the different units of measurement used.
73 Section 6 describes the mathematical models that take into account the latent heat within a green roof energy
74 balance and their main outcomes. In section 7, the main findings derived from research performed using
75 dynamic simulation software are reported. Finally, Section 8 presents the sensitivity analysis conducted by
76 previous studies to determine the influence of the different parameters (volumetric water content, solar
77 radiation, wind velocity, relative humidity, soil thickness, etc.) on the evapotranspiration effect.

78

79 **2. An overview of evapotranspiration in green roofs**

80 During recent years, evapotranspiration (ET) has received a growing interest from the green roof research
81 community because of its impact on heat and mass transfer. This phenomenon is a combination of the water
82 transpired by plants during their growth or retained in the plant tissue (transpiration) plus the moisture
83 evaporated from the soil surface and vegetation (evaporation). On one hand, transpiration is the process by

84 which moisture is carried through plants from roots to small pores on the underside and upper side of leaves,
85 where it changes to vapour and is released to the atmosphere. Transpiration is essentially evaporation of
86 water from plant leaves. Transpiration also includes a process called guttation, which is the loss of water in
87 liquid form from the uninjured leaf or stem of the plant, principally through water stomata. On the other
88 hand, evaporation is the process whereby liquid water is converted into water vapour and is removed from
89 the soil surface. It is the only form of moisture transfer from land and oceans into the atmosphere. These
90 processes are mainly determined by solar irradiation reaching the soil surface as it supplies the necessary
91 energy.

92 The level of the plant development has a considerable influence on the rate of water consumption and in the
93 final energy balance of a green roof system. During the development of complete vegetative cover, the water
94 consumption rate increases rapidly from low to high values. When plants are small, water is mainly lost by
95 evaporation from the soil; later, once the vegetation is well developed and completely covers the soil surface,
96 transpiration becomes the main process. However, the experimental data revealed that ET has a dynamic and
97 complex behaviour that depends on both climatological parameters and soil and vegetation characteristics
98 [32,33].

99 The principal climatological parameters to assess the ET process are: the solar radiation, the wind speed, the
100 air temperature, the relative humidity, and the sky conditions. In addition, ET also depends on the
101 characteristics of both vegetation and soil, principally the degree of shading of the canopy (leaf area and
102 density, LAI) and the amount of water available at the soil surface. In particular, the characteristic of the
103 vegetation that is most important from the standpoint of impacts on the heat transfer through the roof is the
104 leaf area index (LAI). LAI is established as the one-sided green leaf area per unit ground surface area ($LAI =$
105 $\text{leaf area/ground area, m}^2/\text{m}^2$) in broadleaf canopies. The LAI value depends on the type and the growth
106 phase of the plant (crop), usually ranging from 0 to 10. E.g., if the average parcel of roof surface is beneath
107 two leaves, the corresponding LAI is 2. Values of LAI for green roofs vary depending upon plant type, but
108 are typically in the range of 0.5–5.0 [34]. Moreover, the stomatal resistance, the plant height, the
109 development of the vegetation and the transpiration rate of each plant species, determine the aptitude to
110 transfer moisture near to the surface roots and canopy, consequently, these characteristics have also influence
111 on the ET rate.

112 When rain and irrigation are scarce, the water content in the substrate drops and the soil surface dries out.
 113 Thereby, in the absence of water supply the evapotranspiration decreases rapidly and may cease almost
 114 completely within a few days.

115 Table 1 summarizes the climatological and green roof parameters affecting evapotranspiration.

116 *Table 1 Climatological and green roof parameters affecting ET*

Climatological	Canopy	Soil	Management practice
Solar radiation	Degree of shading	Water content	Irrigation regime
Air temperature	Canopy characteristics	Soil characteristics	Cultivation practice
Air humidity	Canopy development		
Wind speed			
Rain			
Sky condition			
Season			

117
 118 The evapotranspiration rate can be obtained by experimental measurements or by means of modelling
 119 approaches. Specific devices and accurate measurements of various physical parameters, or the soil water
 120 balance, are required to determine evapotranspiration.

121 The lysimeter is one of the most widely used equipment to measure evapotranspiration. Such device is made
 122 of a soil volume covered by plants placed in a container hydrologically separated by the surrounding soil.
 123 Lysimeters can be classified as non-weighing and weighing type. The weighing lysimeter is based on the
 124 principle of the mass continuity. The evapotranspiration (ET), expressed in mm, is calculated by Eq. 1 as the
 125 difference among precipitation (P), drainage (D), superficial runoff (O) and the variations in soil water
 126 storage (ΔS) (Figure 1).

127
$$ET = P - D - O \pm \Delta S \quad (1)$$

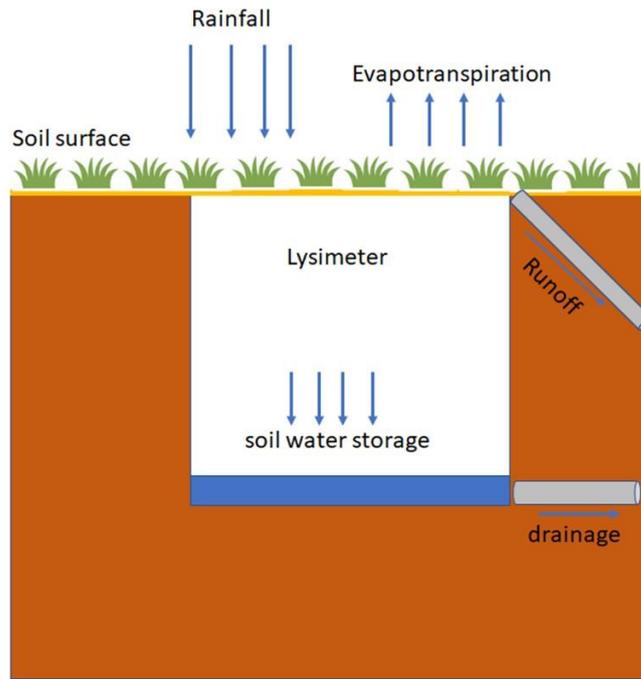


Figure 1 Schematic representation of the soil water balance in weighing lysimeter

128

129

130

131 Weighing lysimeters provide the direct measurements of evapotranspiration over time by monitoring the
 132 evolution of the tray weights (change of mass) due to the water losses. As regard the variation of water
 133 stored (ΔS), it is determined through measurement of the weight change of the soil column over time, with
 134 an accuracy of few hundredths of millimetres. Usually the following equivalence is assumed: $1 \text{ kg} \approx 1 \text{ L m}^{-2}$
 135 $= 1 \text{ mm}$.

136 Non-weighing lysimeters allow determining the evapotranspiration, during a given time period, subtracting
 137 the drainage water collected at the bottom of the lysimeters from the total water input. Actually, few studies
 138 directly quantified ET by measuring the rate of water loss [35], since such method is often expensive and
 139 demanding in terms of accuracy of measurements.

140 In order to predict the evapotranspiration, therefore, numerous numerical methods have been developed
 141 based on climatological data (e.g. temperature, day length, humidity, wind, and solar irradiance) [36]. These
 142 numerical models, such as those of Hargreaves and Allen (2003) [37], Priestley and Taylor (1972) [38],
 143 Penman (1948) [39], and Penman–Monteith [40,41], estimate the so called “potential evapotranspiration”
 144 (PET or ET_0) over bare soil surface or vegetation.

145 Penman (1948) defined PET as the ET from actively growing short green vegetation, completely shading the
 146 ground and never suffering scarcity of moisture availability. Consequently, PET models neglect factors that,

147 conversely, are decisive in the actual evapotranspiration (AET) that occurs under natural field conditions
 148 (i.e., variable soil water contents).

149 Table 2 summarizes the most common models used to evaluate ET. All these previous models are
 150 characterized by a daily time step.

151 *Table 2 Models for estimating evapotranspiration*

Name	Function	Reference
Penman-Monteith (1965)	$ET = \frac{0.408 \Delta (R_n - G) + \frac{\gamma 900}{T_a + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)}$	[39]
Priestley-Taylor (1972)	$ET = \alpha \Delta (R_n - G) / (\Delta + \gamma)$	[38]
Hargreaves (1975)	$ET_0 = 0.0075 R_s T_F$	[37]
Hargreaves (1985)	$ET_0 = 0.0022 R_s (T_a + 17.8) TD^{0.5}$	[37]
FAO-56 Penman-Monteith (1998)	$ET_0 = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{T_a + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)}$	[41]
Penman-Monteith ASCE (2005)	$ET_{sz} = \frac{0.408 \Delta (R_n - G) + \gamma \left(\frac{C_n}{T_a + 273} \right) u_2 (e_s - e_a)}{\Delta + \gamma (1 + C_d u_2)}$	[40]

152
 153 The most known PET model is the Penman-Monteith, which allow estimating the latent heat fluxes at the
 154 vegetation layer that achieve the daily evapotranspiration in a time step, taking into account numerous
 155 physical phenomena and some characteristics of the plants [42]. However, existing evapotranspiration
 156 models have substantial errors for hourly ET predictions over a range of moisture conditions to assess the
 157 hydrological performance of the green roofs during storm events. Therefore, Jahanfar et al. (2018) [43]
 158 developed a modified Penman-Monteith equation to provide improved prediction of hourly
 159 evapotranspiration specifically for green roof applications.

160 Alternatively, the indirect methods calculate the ET through the energy and mass balance equations [44,45].

161 The energy budget method (EBM) is based primarily on the concept that ET is function of the availability of
 162 energy to evaporate water (Q_{ET}), under the hypothesis that the moisture supply is not restricted.

163

164 **3. Climatological parameters influencing ET**

165 The principal meteo-climatic parameters affect the ET by removing water from the plants and soil surface
 166 are solar radiation, wind speed, relative humidity and air temperature, and sky conditions (e.g. cloudy,

167 sunny). These climatic features have both seasonal and geographic variations.

168 3.1. *Solar radiation and seasonal variation*

169 The water depletion rate of soil reflects the solar radiation input that sustains the evapotranspiration.
170 Tabares-Velasco and Srebric (2012) [46] performed a sensitivity analysis in order to understand which
171 parameters greatly affect ET. Among all the environmental variables, solar radiation was the one with the
172 strongest influence on ET. However, ET intensity varies due to the combined effect of solar radiation with
173 the other meteo-climatic parameters.

174 Jim and Tsang (2011) [47] found that the transpiration rate peaked in autumn due to the high level of solar
175 radiation and the low relative humidity. The actual solar radiation reaching the earth surface depends by the
176 turbidity of the atmosphere and the presence of clouds, which reflect and absorb a large percentage of the
177 radiation. Therefore, sky conditions affect ET, since they modify the energy balance of the evaporating
178 surface.

179 Coutts et al. (2013) [48] evaluated the advancement of ET for both a green roof and a bare soil measuring the
180 volumetric water content during four clear sunny summer days. In both vegetated and bare soil, the ET was
181 rather modest, with values of about 50 W/m^2 , suggesting that during the monitored summer period there was
182 scarcity of water available in the soil to support evapotranspiration. Consequently, the cooling effect of the
183 green roofs was significantly restricted. Jim and Peng (2012) [49] differentiated the sky conditions into three
184 types: sunny, cloudy and rainy. Overall, sunny days registered progressive water loss from the substrate due
185 to evapotranspiration, while during cloudy days the evapotranspiration was low so the water was maintained
186 in the substrate. Moreover, the ET was correlated with the volume of water contained in the substrate,
187 distinguishing between moist and dry substrates. For each weather type, wet means that the moisture content
188 is at or near the maximum daily initial moisture level; moist means at or near the average daily initial
189 moisture level; and dry means at or near the minimal daily initial moisture level. Thus during cloudy days
190 both moist and dry substrate recorded similar evapotranspiration, while during sunny days the dry substrate
191 recorded an even higher evapotranspiration than the moist.

192 Otherwise, Lazzarin et al. (2005) [50] compared the ET in dry and wet soil in summer and observed that the
193 wet soil gave rise to higher evapotranspiration whereas in dry conditions that contribution was limited. In

194 winter, despite the considerably lower solar irradiance in comparison to the summer season, the
 195 evapotranspiration flux was also appreciable. During summer, with the soil in almost dry conditions the
 196 green roof allowed an attenuation of the thermal gain entering the underneath room of about 60% with
 197 respect to a traditional roofing with an insulating layer. During the winter the evapotranspiration process was
 198 driven above all by the air vapour pressure deficit; it is not negligible weight produced an outgoing thermal
 199 flux from the roof that was 40% higher than the corresponding one of a high solar absorbing and insulated
 200 roofing.

201 Jim and Tsang (2011) [47] found that the seasonal transpiration rates on sunny days were, in descending
 202 sequence: autumn, summer, winter and spring. They suggested that the relatively high transpiration rate
 203 observed in summer sunny days occurs because high solar radiation and air temperatures promote
 204 photosynthesis. In winter sunny days, the transpiration rate was lower than in autumn and summer because
 205 of the solar radiation is less intense. Such result was confirmed by the modest transpiration rate observed in
 206 spring, the lowest recorded in this study, which were due to weak solar radiation and low temperatures
 207 characterizing this season.

208 In the study performed by Lee and Jim (2018) [51], the progressive dropping of air and green roof surface
 209 temperatures in the course of the sunny day was explained by the effective cooling brought by
 210 evapotranspiration fuelled by solar radiation input. Even though irradiance at the green roof surface was
 211 limited, the ambient warmth and relatively low surface temperature did not require a lot of latent heat
 212 absorption to cool down.

213 As shown in Table 3, most of the analysed studies evaluated ET during summer periods when it is expected
 214 to be higher in comparison to winter periods, due to the influence of solar radiation and relative humidity.
 215 Since sky conditions influence on the final ET process, it is important to highlight the scarce literature (6
 216 over 21) that provide a proper description of the weather conditions.

217 *Table 3. Classification of the studies reviewed according to the season, sky conditions and climate classification*

References	Köppen classification	Weather	Season	Type of study
Feng et al. [52]	Cfa	-	Summer	Modelling
Jim and Peng [49]	Cwa	Sunny-cloudy-rainy	Summer	Experimental
Jim and Tsang [47]	Cwa	Sunny-cloudy-rainy	Whole year	-
Lazzarin et al. [50]	Cfa	-	Summer-winter	Modelling
He et al. [53]	Cfa	Clear-cloudy-rainy	Summer	Modelling
Tabares-Velasco and Srebric [54]	-	-	Summer	Experimental

Tabares-Velasco and Srebric [46]	-	-	Summer	Modelling
Ouldboukhitine et al. [55]	Cfb	-	Summer	Experimental
Coutts et al. [48]	Cfb	Sunny	Summer	Experimental
Schweitzer and Erell [56]	Csa	-	Summer-winter	Experimental
Ouldboukhitine et al. [57]	Cfb	-	Summer	Experimental
Tan et al. [58]	Af	-	Summer-winter	Experimental
Tian et al. [59]	Cfa	-	Summer	Modelling
Hodo-Abalo et al. [60]	-	Sunny	-	Modelling
Tsang and Jim [61]	Cwa	Sunny-cloudy	Summer	Modelling
Ouldboukhitine et al. [62]	-	Sunny	Summer	Modelling
Boafo et al. [63]	Dwa	-	Summer-winter	Simulation
Silva et al. [64]	Csa	-	Summer-winter	Simulation
Vera et al. [65]	Bsk			
	Csc	-	Summer	Simulation
	Cfb			
Lee and Jim [51]	Cwa	Sunny-cloudy-rainy	Summer	Experimental

218

219 The previous survey indicates that the solar radiation is the climatic data with the strongest correlation with
 220 evapotranspiration [49]. Such correlation will be further analysed in Section 8, assessing previous sensitivity
 221 analyses.

222 Otherwise, since the ET phenomena depends also by the whole meteo-climatic features, future studies have
 223 to include as much possible complete meteo-climatic description in order to correlate the ET with the main
 224 climatic conditions (e.g. sunny, cloudy and rainy days). Furthermore, because of the lack of studies that
 225 cover the ET during an entire year, further experimental studies should include a whole year analysis in order
 226 to evaluate the ET in the different seasons and in different weather conditions.

227 3.2. *Wind speed*

228 The process of vapour removal also depends by the air turbulence, which increase the convective heat fluxes
 229 between the atmosphere and the soil surface, as well as the airflow over the soil surface. Continuous
 230 vaporization of water by means of ET leads the air above the soil surface to become gradually saturated. If
 231 this vapour is not continuously replaced with drier air, the driving force for water vapour removal and ET
 232 decrease. Intense wind improved the transport not only of heat but also of water vapour, increasing the
 233 evapotranspiration fluxes.

234 Schweitzer and Erell (2014) [56] compared the total daily evapotranspiration for four plant species during
 235 days with weak ($2 \text{ m}\cdot\text{s}^{-1}$) and strong wind ($5 \text{ m}\cdot\text{s}^{-1}$). The authors concluded that there were substantial
 236 differences among the plant species, i.e. the vegetated roof with *Aptenia* losing less than half as much water

237 as the vegetated roof with *Halimione*, about $3.0 \text{ L}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ compared to $7.5 \text{ L}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ under low wind
238 conditions ($2 \text{ m}\cdot\text{s}^{-1}$). This rate was even less than for exposed moist soil, i.e. without plants, about 3.8
239 $\text{L}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$. The other two species analysed, *Pennisetum* and *Sesuvium*, reached intermediate value, about
240 $7.0 \text{ L}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$. In windy conditions ($5 \text{ m}\cdot\text{s}^{-1}$), the maximum hourly loss for *Pennisetum* was nearly 2.0
241 $\text{L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$, and the daily total was over $9.0 \text{ L}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$. *Sesuvium*, moist soil, *Aptenia* and *Halimione* reached
242 lower values of evapotranspiration, 8.8 , 6.0 , 5.8 and $4.0 \text{ L}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$, respectively. In this study, high wind
243 speed enhanced the ET.

244 In another experiment, Tabares-Velasco and Srebric (2011) [54] found that when the wind speed varied from
245 $0.1 \text{ m}\cdot\text{s}^{-1}$ to $1.0 \text{ m}\cdot\text{s}^{-1}$ the evapotranspiration rate increased from 10% to 30%. This result confirm that air
246 convection effectively brings water vapour from the soil or foliage to the atmosphere increasing the
247 evapotranspiration rate.

248 For instance, an increase of the convection coefficient, which has a direct correlation with wind velocity,
249 from 12.0 to $16.0 \text{ W}/\text{m}^2\text{K}$ reduce the heat storage by 24% and 45% for bare and green roofs, respectively
250 [61].

251 Jim and Tsang (2011) [47] found a rather modest correlation between the wind above the canopy and
252 transpiration, so the wind should not play a major role in facilitating the transpiration rate. Figure 2 shows
253 the sunny and rainy wind speed measured at canopy top in [47]. The wind speed was relatively higher on
254 rainy days than on sunny ones. The wind speed on rainy and sunny days averaged at 3 ms^{-1} and 1 ms^{-1}
255 respectively. The correlation coefficients between wind and transpiration at -0.1 to 0.1 ($p \leq 0.05$) was
256 weak. Although wind speed was higher on rainy days, the associated high relative humidity suppresses
257 transpiration.

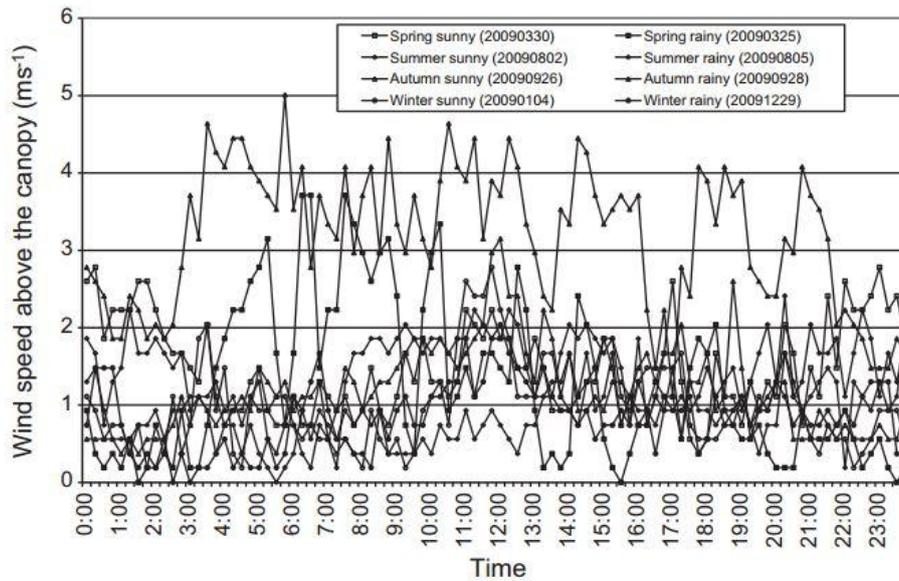


Figure 2. Seasonal and diurnal wind speed above the canopy of the sky woodland [47]

258

259

260 3.3. Relative humidity and air temperature

261 Even if the energy supplied by the solar radiation is the main driving force for the vaporization of water, the
 262 difference between the water vapour pressure at the soil and plants surface, and the surrounding air are other
 263 important factors that also determine the vapour removal.

264 High temperatures combined with lower relative humidity (RH) enhance the evapotranspiration process [66].
 265 Tabares-Velasco and Srebric (2012) [46] stated that ET was strongly influenced by the environmental
 266 conditions, in terms of air temperature and relative humidity in the vicinity of the green roof.

267 Generally, during night-time the outdoor air reach low temperatures that conversely cause the increase of RH
 268 until 100%, so reducing the ET process. On the contrary, during day-time the higher air temperature induces
 269 a fall of RH so allowing the evaporative process to take place [49].

270 In a Cwa climatic area where the relative humidity and the air temperature varied between 50%, 23 °C in
 271 autumn, and 80%, 36 °C in summer, Jim and Tsang (2011) [47] found that the highest transpiration rate is
 272 observed in autumn rather than in summer, because of low relative humidity and mild air temperature.
 273 According to this study, evapotranspiration is minimized in a humid environment and the high relative
 274 humidity is the crucial factor that dampens the transpiration rate.

275 Unlike the green roof in the temperate region, the experiment carried out by Jim and Tsang [47] showed that
 276 the transpiration rate of an intensive green roof in the humid-subtropical region, dominated by the Monsoon
 277 climate system, depends mainly on photosynthetically active radiation and relative humidity.

278 As with all the other processes that take advantage of evaporation, planted roofs do not have much to offer in
 279 terms of ET rate in a humid environment compared with an arid one [50].

280 3.4. Irrigation regime

281 Azeñas et al. (2018) [67] analysed the relationship between irrigation regime and heat flux through green
 282 roofs. In particular, the authors considered well-watered and water-limited condition. Surface drip irrigation
 283 at 50% and 25% of potential evapotranspiration (ET_0) was applied twice a week during the calculated time
 284 according to the nominal drippers flow (2 l h^{-1} for each dripper) and considering the number of drippers (9
 285 drippers for each module). Results showed lower heat flux in water-limited than in well-watered treatments
 286 in both non-vegetated and vegetated modules, suggesting that the lower heat transfer with air in comparison
 287 to water would counteract the cooling effect of evapotranspiration that is supposed to be higher in the well-
 288 watered modules, where the volumetric water content is higher. In particular, water-limited irrigation
 289 treatment was shown to increase the thermal insulation capacity when compared to complete well-watered
 290 irrigation treatment, by reducing the total transferred heat between 25% and 71% along the different seasons
 291 of the year, suggesting that the air/water substrate content has a greater effect on insulation than
 292 evapotranspiration.

293 3.5. The geographic area

294 The review conducted by Pérez et al. (2014) [68] concluded that the Köppen climate classification is the
 295 most suitable reference to compare research results about green infrastructures. In order to provide a
 296 continuous framework in the literature, this review used the same climate classification for all the reviewed
 297 papers (Table 4).

298 *Table 4. Climate classification of experimental, modelling and simulation studies*

Ref.	Authors	Year	Location		Climate according to the author	Köppen classification
[49]	Jim and Peng	2012	Hong Kong	Hong Kong	Humid-subtropical	Cwa
[69]	Takebayashi and Moriyama	2007	Japan	Kobe	-	Cfa
[54]	Tabares-Velasco and Srebric	2011	USA	Pennsylvania	-	Dfb
[46]	Tabares-Velasco and Srebric	2012	USA	Pennsylvania	-	Dfb
[55]	Ouldboukhitine et al.	2012	France	La Rochelle	-	Cfb
[48]	Coutts et al.	2013	Australia	Melbourne	-	Cfb

[56]	Schweitzer and Erell	2014	Israel	Tel Aviv	Mediterranean	Csa
[57]	Ouldboukhitine et al.	2014	France	La Rochelle	-	Cfb
[58]	Tan et al.	2017	Singapore	Singapore	-	Af
[52]	Feng et al.	2010	China	Guangzhou	-	Cfa
[70]	Djedjig et al.	2012	France	La Rochelle	-	Cfb
[69]	Takebayashi and Moriyama	2007	Japan	Kobe	-	Cfa
[50]	Lazzarin et al.	2005	Italy	Vicenza	-	Cfa
[53]	He et al.	2016	China	Shanghai	North subtropical monsoon	Cfa
[46]	Tabares-Velasco and Srebric	2012	USA	Pennsylvania	-	Dfb
[59]	Tian et al.	2017	China	Chongqing	Humid subtropical monsoon	Cfa
[60]	Hodo-Abalo et al.	2012	Togo	-	-	Aw
[61]	Tsang and Jim	2011	Hong Kong	Hong Kong	-	Cwa
[62]	Ouldboukhitine et al.	2011	France	La Rochelle	-	Cfb
[63]	Boafo et al.	2017	Republic of Korea	Incheon	Humid continental	Dwa
[64]	Silva et al.	2016	Portugal	Lisbon	Mediterranean	Csa
			USA	Albuquerque	Semi-arid	Bsk
[65]	Vera et al.	2017	Chile	Santiago	Semi-arid	Csc
			Australia	Melbourne	Marine	Cfb

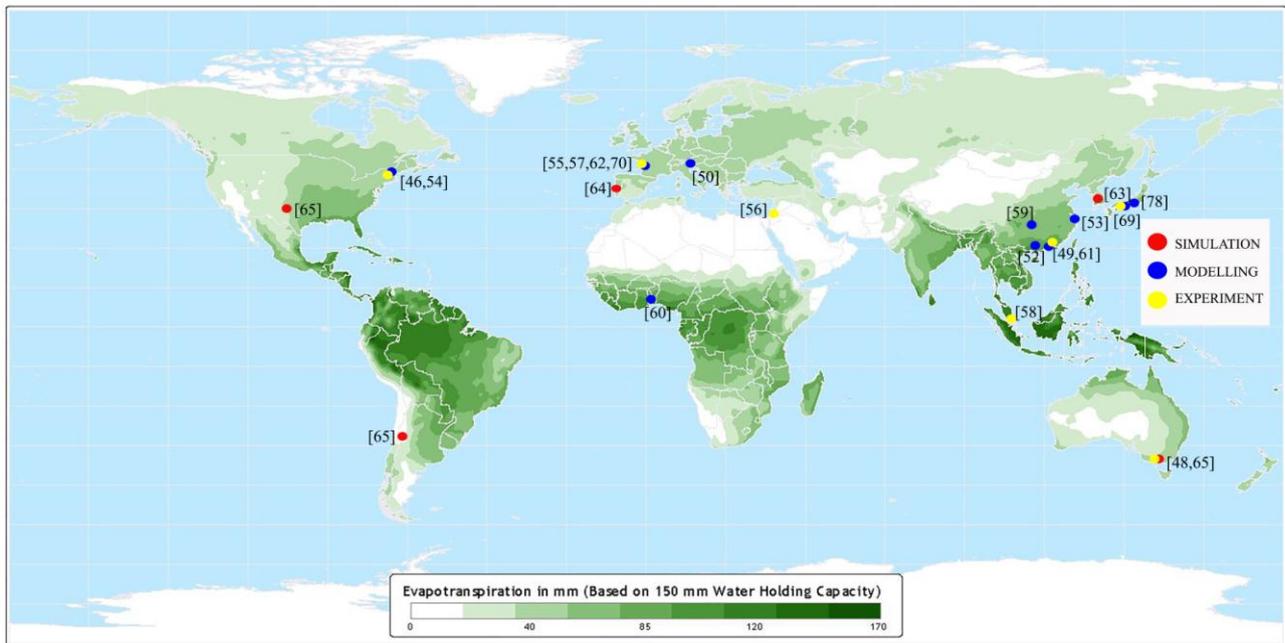
299

300 Most of the studies reviewed in this paper (71%) were carried out considering temperate climatic conditions,
 301 first letter C according to the Köppen classification. About 17%, 8% and 4% of the studies were developed
 302 in tropical (D), arid (A) and cold climates (B), respectively.

303 The 71% of the studies performed in temperate climates are located in areas without dry seasons (Cf
 304 according to the Köppen classification). About 17% of these studies were performed in climates with dry
 305 summers, second letter s (Cs according to the Köppen classification). Finally, only a few of the studies
 306 analysed, about 12%, are located in climates with dry winters, second letter w (Cw according to the Köppen
 307 classification).

308 Figure 3 shows the analysed studies located on the world evapotranspiration map. The Water Holding
 309 Capacity is the total amount of water available for plants that is held against gravity in a soil and is usually
 310 estimated as the amount present at -0.03 MPa average water potential minus the amount present at -1.5 MPa
 311 water potential. In [71], the authors stated that it is a very important soil characteristic strongly and positively
 312 correlated to the inherent productivity of soils.

313 Most of the studies were performed in the western part of the world under temperate climatic conditions
 314 (Figure 3). However, other regions could allow achieving high rates of ET that have not yet deeply explored
 315 or at least there is a lack of data in literature. Consequently, future studies should encompass experimental
 316 study in tropical and arid climates where green roofs could enhance the cooling effect on buildings thanks
 317 the potential high ET rates.



318
 319 *Figure 3. Location of simulation, modelling and experiment studies in the world Evapotranspiration map [72]*

320
 321 However, it has to be underlined as in hot arid regions green roofs need to be well watered, due to the
 322 abundance of solar energy and dry air, consequently they consume large amounts of water. On the other
 323 hand, in humid tropical regions, since the air is frequently close to saturation, less additional water can be
 324 transferred from the green roof to the atmosphere, and hence the evapotranspiration rate is lower than in arid
 325 regions.

326 The world evapotranspiration map presented in Figure 3 is obtained by considering all the environmental
 327 parameters of a specific geographic area affecting natural evapotranspiration, such as solar radiation, relative
 328 humidity, annual average temperatures and annual average precipitation, which are the most important
 329 parameters for the vegetation development.

330 In some geographic areas of the world presented in Figure 3, such as in the African desert area, where
 331 potential evapotranspiration is high due to solar radiation and air temperatures, there is no evapotranspiration
 332 due to the lack of water. Therefore, if there were enough amounts of natural water (e.g. rain and water wells),

333 these geographic areas could be enabled to take advantage of the cooling effect of green roofs.
334 An analysis of Figure 3 underlines that further experimental studies about ET should be carried out in
335 regions of the world that have not been yet deeply investigated.

336 It is worth mentioning that the ET in green roofs differs from the phenomenon of natural evapotranspiration
337 since, in addition to the above-mentioned climatic variables, it is also affected by the inherent properties of a
338 green roof system. Some of these properties are; type of plants, substrate characteristics (thickness and
339 composition), and irrigation regime that provides water for evapotranspiration in the absence of precipitation.

340

341 **4. Plant-substrate parameters influencing ET**

342 *4.1. Volumetric water content*

343 The cooling performance of a green roof depends on the water content of the substrate that determines the
344 availability of water for evapotranspiration. Volumetric water content in the soil is related to the green-roof
345 hydrological cycle because the green roof gains water from rainfall and irrigation, and loses it through
346 evapotranspiration, surface runoff and drainage.

347 Djedjig et al. (2012) [70] found that when the green roof was characterized by a VWC in the soil of 10% of
348 the maximum value, evapotranspiration was reduced to its minimum. On the contrary, evapotranspiration
349 increased when the substrate had high water content.

350 Jim and Peng (2012) [49] found that during rainy days, antecedent VWC in the soil reduces the infiltration
351 rate, thus increasing the runoff quantity. On successive sunny or cloudy days when drainage and run-off are
352 negligible, the water stored in the substrate depends by irrigation and evapotranspiration. Previous studies
353 [27,73,74] identified volumetric water content in the soil as the key factor for the evapotranspiration process,
354 especially when irrigation is not present. In Bevilacqua et al. (2015) [75] even though the environmental
355 conditions would allow evapotranspiration to take place, no considerable ET was found due to the limited
356 water content in the substrate.

357 In the research conducted by Tan et al. (2017) [58] on conventional garden soil and artificial substrates,
358 consisting mainly of perlite, the evapotranspiration rates exhibited strong positive correlations with the
359 volumetric water content. In fact, when volumetric water content in the soil decreased gradually, the plant

360 evapotranspiration rate was restricted. In addition, the ET decreased because of the low plant transpiration
361 activity due to the lack of available water even if high solar irradiance occurred.

362 The use of a water retention layer below the green roof substrate makes it possible to maintain the VWC
363 consistently higher. The water retention layer, therefore, sustains plant life by providing an additional
364 availability of moisture, i.e. a liquid such as water in the form of very small drops, either in the air, in a
365 substance, or on a surface. In green roof systems planted with *Sedum mexicanum* and *Disphyma austral*,
366 Voyde et al. (2010) [35] observed a rapid water loss via latent heat flux in the days after watering. This water
367 loss gradually decreased because the water available was reduced until plants stopped transpiring to preserve
368 water.

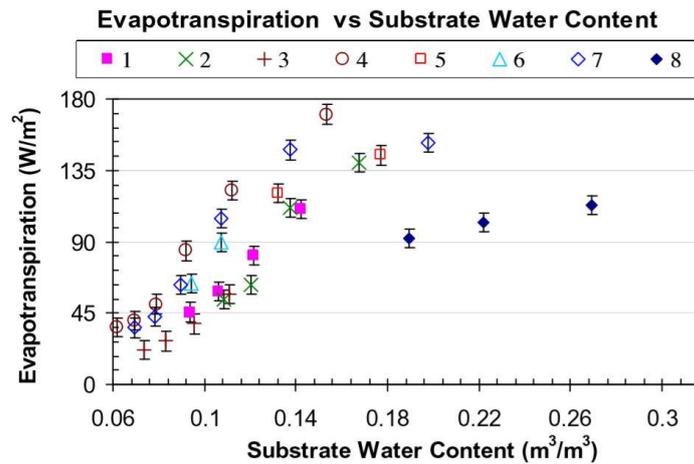
369 The sensitivity test performed by Feng et al. (2010) [52] has shown that an increase from 30% to 60% in
370 volumetric water content in the soil showed a reduction of 24% the heat stored within the green roofs, thanks
371 to the increasing latent heat. On the contrary, Tabares-Velasco and Srebric (2012) [46] found that the water
372 content in the substrate did not have the most significant impact on ET. However, a change in substrate
373 conditions from the driest to the wettest led to a decrease in the substrate temperature of about 10.0 °C and a
374 reduction in the incoming heat flux by 40%. This reduction was mainly due to an increase in the
375 evapotranspiration rate (from 8.0 to 230.0 W/m²) despite of an increase of 70% in substrate thermal
376 conductivity and a decrease of 50% in substrate reflectivity, measured with a Portable Spectroradiometer
377 using a calibrated lamp different that the fluorescent lamps directly above plants. Soil reflectivity depends on
378 soil type and water content that typically varies from 0.10 for wet soil to 0.35 for dry soil.

379 He et al. (2017) [76] found that a higher water ratio helped to increase the evapotranspiration intensity while
380 it decreased the thermal resistance of soil layer. As it was evaluated in some studies, the relation between the
381 increment in the substrate volumetric water content and the increment of ET was not linear [49,54].

382 Evapotranspiration-substrate water content curves have an elongated “S” shape with low evapotranspiration
383 rates when water is scarce in the substrate and high evapotranspiration rates when water is abundant. In the
384 middle of the substrate water content range, the relationship is approximately linear (Figure 4). Experimental
385 data revealed that samples with higher water content provided higher latent fluxes and lower convective
386 fluxes [52].

387 As result this section highlight that substrate water content plays an important role in decreasing

388 temperatures on the green roof surface and the total incoming heat flux through the roof.



389
390 Figure 4. Relationship between evapotranspiration and substrate water content [54]

391

392 4.2. Vegetation

393 The transpiration process of plants contributes to the evaporation from the substrate, moreover the plant layer
394 shades the roof surface and further reduces the heat fluxes incoming into the roof.

395 The species of plants, their physiology and growth typology, influence the green roof cooling effect by
396 means of the ET process. Succulent plants, which store excess water in their thick leaves, are generally well
397 adapted to extreme climates, and particularly in dry conditions. The *Sedum* family, capable of activating
398 *Crassulacean Acid Metabolism* (CAM) photosynthesis, is recommended for extensive roofs where the depth
399 of the soil layer is very shallow [77]. Under dry soil conditions, the evapotranspiration in a green roof with
400 *Sedum* may be mostly evaporation from soil, with little transpiration from plants. Voyde et al. (2010) [35]
401 found that planted treatments of *Sedum mexicanum* and *Disphyma australe* attained a latent heat flux of 2.19
402 mm/day and 2.21 mm/day, respectively, when the plants were not water stressed. Irrigated green roofs
403 showed a latent heat flux higher than 200 W·m⁻², suggesting that despite the presence of drought-tolerant
404 *Sedum*, irrigation increased evapotranspiration when water was available.

405 Schweitzer and Erell (2014) [56] compared a well-watered roof covered with and without plants and
406 observed that ET was the least effective cooling mechanism without the shade provided by plants. *Aptenia*
407 lost less than half as much water as *Pennisetum*, about 3 L m⁻²day⁻¹ and 7 L m⁻² day⁻¹ respectively. The
408 *Pennisetum* loss rate was even less than in bare moist soil, about 3.8 L m⁻² day⁻¹. Coutts et al. (2013) [48]
409 evidenced that soil without plants may deliver greater latent heat fluxes, as the resistance to water loss from

410 the vegetation surface is not present. The peaks of latent heat flux afterwards a cycle of irrigation are lower
411 on the green roofs than the bare soil, this because the green roofs retained water in the substrate and
412 vegetation over a longer period. The samples with plants consistently show an average reduction of the heat
413 flux transferred into the spaces beneath the roof of about 25% compared to samples without plants. This is
414 because plants provide extra shading to the roof, additional water storage, and a better water control by
415 means of evapotranspiration and photosynthesis [54].

416 It was found that the Leaf Area Index (LAI) factor and the amount of evapotranspiration from the top surface
417 have a large effect on the heat flow transferred into the spaces beneath the roof [78]. In a Mediterranean
418 climate, results have shown that the LAI greatly influences the thermal performance of the vegetated roof
419 since it enhances shading, convective heat transfer, and evapotranspiration. Higher LAI values allow to
420 achieve higher cooling effect due to the increase of evapotranspiration [79,80].

421 Tabares-Velasco and Srebric (2012) [46] pointed out that among the green roof design variables, the most
422 significant factor that allowed a reduction in temperature and heat flux through the substrate was the LAI.

423 In agreement with the findings obtained by Tabares-Velasco and Srebric [62], Hodo-Abalo et al. (2012) [60]
424 found that evapotranspiration is more intense when the foliage is sufficiently dense. In addition, the LAI has
425 important effects on the energy phenomena in the vegetation layer, thanks to the shading and transpiration
426 that it provides, reducing solar flux penetration, stabilizing fluctuating values and reducing the indoor
427 temperature.

428 Theodosiou (2003) [66] revealed large heat flows from the substrate surface to the atmosphere for surfaces
429 on sunny days and relatively small flows on cloudy days, when the value of LAI was up to 3.0. Therefore,
430 under such operative conditions there was a significant increase the cooling effect on the room space. It was
431 an office building. The floor beneath the planted roof had an area of 70 m², internal gains of 1.10 kWh
432 during working hours (08:00–16:0 h) and 0.1 kWh during the rest of the day. The air conditioning functions
433 during the 8 h period with a thermostat set at 26 °C and.

434 Lee and Jim (2018) [51] concluded that the dense foliage of the woodland vegetation should have provided
435 greater shading and evapotranspirative cooling than an Indian green roof with herbaceous vegetation but 0.4
436 m-deep substrate used by Kumar and Kaushik (2005) [81]. The green roof used in [51] achieved only half
437 the maximum air temperature of 12 °C on the Indian intensive green roof. The authors concluded that such

438 disparity could be caused by variations in vegetation characteristics.

439 4.3. Stomatal resistance

440 Plant transpiration or latent heat flux depends on the physiological properties of the plants and their stomatal
441 resistance or conductance that controls water loss. Stomatal resistance is opposed to the transport of water
442 vapour and carbon dioxide to or from the stomata on the leaves of plants, the lower the value of stomatal
443 resistance, the greater the ET. It depends by the water content in the interior of the stomata cavity and on the
444 exterior surface of the leaf, but also by air density and moisture flux.

445 The dimension of stomatal resistance is time over distance that is the inverse of velocity, its values depend
446 on plant selection. Grass plants with stomatal resistance of $60 \text{ s}\cdot\text{m}^{-1}$ produce evapotranspiration fluxes that
447 are 3-4 times higher than those produced by succulent plants (e.g. *Sedum*) [46].

448 Generally, plant species with low values of stomatal resistance allow achieving higher ET if there is
449 sufficient water in the soil.

450 4.4. Stomatal conductance

451 Otherwise, the stomatal conductance gives an estimation of the rate of exchange of gases and transpiration
452 through the stomata of the plants, which depends by solar radiation, temperature, humidity and water
453 availability. Higher stomatal conductance tends to correspond to higher evapotranspiration rates. The
454 stomatal conductance is usual measured in $\text{mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.

455 Tan et al. (2017) [58] have studied the variation of the stomatal conductance of *Cyathula prostrata* in
456 function of both the cycle of irrigations and the type of soil (i.e. artificial soil, consisting mainly of perlite,
457 and normal garden soil), which is a commercially available soil mix commonly used in urban landscapes. It
458 was observed that during periods of regular irrigation, average stomatal conductance of *Cyathula prostrata*,
459 which is a creeping shrub, was about $600.0 \text{ mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. When irrigation was withheld, the stomatal
460 conductance of *Cyathula prostrata* planted into the artificial soil was reduced to around $100.0 \text{ mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$,
461 while in a normal garden soil the stomatal conductance was reduced to $50.0 \text{ mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. For the case of the
462 artificial soil equipped with a water retention layer, when irrigation was withheld the stomatal conductance
463 slightly reduced to $425 \text{ mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. When irrigation was resumed, stomatal conductance levels increased

464 to $375.0 \text{ mmol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ both in the case of artificial and normal garden soil.

465 This section has highlighted that the choice of the type of plants entails to different stomatal conductance,
466 which in turns affects the ET.

467 4.5. *The substrate and drainage layer*

468 Several studies [33,82,83] have revealed that the characteristics of the substrate and drainage layer affect the
469 evapotranspiration phenomena in the green roof.

470 The characteristics of the substrates that influence evapotranspiration are porosity, size of the soil particles,
471 compaction of the material and permeability (or hydraulic conductivity), as well as the thickness of the
472 material. Several studies have investigated the thermo-physical and hydrological properties of different types
473 of substrate [84,85], which could be constituted of both organic and inorganic material.

474 However, less attention was paid in assessing the impact of the drainage layer on the green roof
475 evapotranspiration, although the evapotranspiration varies considerably depending on the type of solution
476 adopted for the drainage layer. The most common solutions used as drainage layers in green roofs are
477 constituted by modular plastic panels with a water retention layer, or in alternative by natural granular
478 materials such as expanded clay, pumice, natural pozzolana, perlite, etc. Recently new granular materials
479 deriving, in whole or in part, from the recycling of materials have been proposed as drainage layer [86,87].

480 The benefits derived by the use of such materials are their low environmental impact, in terms of reduction
481 of natural resource consumptions in comparison to traditional drainage layer materials [88].

482 Regarding different types of substrates for green roofs, Tan et al. (2017) [67] have analysed the performance
483 of an artificial substrate characterized by a higher porosity compared to a garden soil, which drain water
484 faster than topsoil (natural soil). Hence, when irrigation was being withheld, less water was available for
485 transpiration or evaporation from the substrate. As consequences, lower volumetric water content and
486 evapotranspiration rates were experimented in this artificial soil compared to a normal garden soil.

487 Getter et al. (2011) [89] suggested that increasing substrate depth would allow the use of plants with greater
488 biomass and leaf area, leading to a higher latent heat flux. In the thin substrate of common extensive green
489 roofs, due to the limited substrate mass effect, solar energy heating the whole substrate increasing its
490 temperature, which in turn increase the evapotranspiration and the water depletion [49].

491 However, it has to be reminded that when the VWC decreases below specific threshold also the ET is
 492 reduced.

493 This section has highlighted how the substrate and the drainage layers affects the ET. Generally, artificial
 494 soil characterized by higher porosity drain water faster than topsoil (natural soil). Hence, when irrigation is
 495 withheld less water is available for transpiration or evaporation from the substrate.

496

497 **5. Equipment used in the reviewed green roof set-ups**

498 Evapotranspiration is difficult to measure in a direct way, since it is a complex physical-physiological
 499 phenomenon that depends on both the phase change of the water contained in the substrate and the
 500 physiological processes occurring in the plant species used in green roofs.

501 As a result, several studies [47,49,52,69,70] have estimated the evapotranspiration rate from plants and soil
 502 through data derived from the substrate water content (“indirect” measurements). Sensors located at different
 503 depths of the soil layer measured the volumetric water content (VWC). Other studies carried out by Lazzarin
 504 et al. (2005) [50], and He et al. (2016) [53] have used the volumetric water content in the soil to calculate the
 505 heat transfer model of green roofs.

506 Table 5 summarizes the main equipment used to evaluate ET and the monitoring periods adopted in literature
 507 studies reviewed. On one hand, the “indirect” measurements presented within this table refer to ET
 508 estimation using data derived from the substrate water content. In this case, the water content variation is
 509 assumed equal to the ET. On the other hand, “direct” measurements refer to ET estimation using data
 510 collected by a lysimeter or load cells, monitoring the evolution of sample weight and not the water content
 511 variation in the substrate.

512 *Table 5. Summary of the main instrumentation used in the reviewed set-ups and the length of monitoring periods*

References	VWC sensor	Load balance	Portable closed chamber	Indoor test	Outdoor test	Monitoring period	Type of measurements
[52]	X	-	-	-	X	11 days	Indirect
[49]	X	-	-	-	X	2 months	Indirect
[70]	X	-	-	-	X	3 weeks	Indirect
[69]	X	-	-	-	X	1 month	Indirect
[47]	X	-	-	-	X	1 day	Indirect
[50]	X	-	-	-	X	2 months	Indirect

[53]	X	-	-	-	X	2 weeks	Indirect
[90]	X	-	-	X	-	6 days	Indirect
[54]	X	X	-	X	-	2-6 days	Direct and indirect
[46]	X	X	-	X	-	2-6 days	Direct and indirect
[55]	-	X	-	X	-	7 days	Direct
[48]	X	-	X	-	X	4 days	Direct and indirect
[56]	-	X	-	X	-	1 day	Direct
[57]	-	X	-	X	-	Two days	Direct
[58]	X	X	-	-	X	2 months	Direct and indirect

513

514 The devices used for evaluating ET depend on the aim of the research. In fact, if the objective is to validate
515 an energy and mass balance model, researchers have frequently used volumetric water content sensors. On
516 the other hand, when the aim of the research consists in estimating the rate of evapotranspiration, high
517 precision scales combined with volumetric water content sensors are commonly used.

518 Most of the studies that used load cells were carried out in a laboratory (indoor test) set-up installing samples
519 with reduced size, while only a few studies evaluated ET directly in-situ (outdoor test)[48,58]. Finally, the
520 monitoring period varied widely, from one day to two months (see in Table 5). An important gap in the
521 literature review is detected since the duration of almost all experimental studies (12 over 16) do not provide
522 long periods of measurement (shorter than one month) that include the ET behaviour within the different
523 seasons of a specific climate. Only four studies [49,50,58,69] overcome the duration of a month period
524 monitoring. Besides the experimental set-ups of the following studies [46,50,52,70] were basically used for
525 validating numerical models, they also contributed in providing methodologies to evaluate ET at both levels,
526 theoretical and experimental.

527 In the following, a brief description of the different sensors and devices used for the ET measurement in
528 previous experimental studies is given.

529 Schweitzer and Erell (2014) [56] associated the water consumption in extensive green roofs to the ET
530 process, using mini-lysimeters. Ouldboukhitine et al. (2014) [57] evaluated the amount of water transpired
531 by the plants using wind tunnel to control the wind speed. The hydrologic transfer was measured using a load
532 cell installed under two green roof tray to track the weight loss due to water evapotranspired during the test.

533 The only difference between the two samples was that one of them was planted with vegetation and the other
534 without. While water was evapotranspired by the test trays with vegetation, it was only evaporated by the
535 tray without vegetation. The difference between the two trays allowed an estimation of the quantity of water
536 transpired by the plants. Ouldboukhitine et al. (2012) [55] measured the amount of water lost by
537 evapotranspiration and its impact on the prediction of water content variations using a setup to measure the
538 weight of trays suspended on the traction-compression sensor balance.

539 Liang Tan et al. (2017) [58] evaluated ET by using both direct (with load cell) and indirect methods (with
540 volumetric water content sensors). In such study, the authors divided green roof plots into three treatment
541 combinations characterized by different substrate type as well as the adoption of the water retention layer or
542 not. Sensors were embedded at 0.1 m depth in the middle planters in order to monitor volumetric water
543 content in the soil for each of the set-ups; then, evapotranspiration was measured by weighing the middle
544 planter box. Coutts et al. (2013) [48] used a portable closed-chamber to measure evapotranspiration rates
545 from green roof and soil without vegetation. With this method, chambers restrict the volume of air available
546 for the exchange between the surface and the atmosphere and the net emission or uptake of gases can be
547 measured as a change of water concentration. The latent heat flux, therefore, was determined from the
548 change in the mass concentration of water over time. Green roof samples were also instrumented with
549 volumetric water content into the soil probe at a depth of 0.08 m.

550 Ayata et al. (2011) [90], Tabares-Velasco and Srebric (2011, 2012) [46,54] evaluated evapotranspiration
551 rates by tracking continuously both, the variations in weight of the green roof sample with high-resolution
552 load cells, and the changes in the volumetric water content of the substrate. In these studies, the total water
553 loss measured with the water balance method were 10–20% larger than the load cell. Thus, the authors used
554 evapotranspiration data measured directly from the load cell to validate the heat transfer model proposed.

555 At the end of this survey, it is possible to observe that load cell is the most widely used device for assessing
556 in a direct way the evapotranspiration in green roofs. Thus, such equipment could be recommended in future
557 studies on ET.

558 *5.1. Units of measurement used for expressing the evapotranspiration rate*

559 The evapotranspiration rate is frequently expressed in millimetres (mm) per unit time. The rate expresses the
 560 amount of water lost from a cropped surface in units of water depth. Furthermore, the time unit has large
 561 variability, it can be assumed equal to an hour, day, ten-day period, month or even an entire growing period.

562 The evapotranspiration rate can be stated or in terms of the energy necessary for the water evaporation,
 563 namely the latent heat of vaporization (L_e), expressed in $\text{MJ m}^{-2} \text{ day}^{-1}$, or, using the lysimeter (load cell) to
 564 evaluate evapotranspiration by monitoring the evolution of the tray weights due to water loss over time,
 565 expressed the evapotranspiration in $\text{kg m}^{-2} \text{ day}^{-1}$.

566 Thus, a plethora of units of measurement are used to express evapotranspiration (mm, kg, W/m^2 , etc.), so it
 567 becomes rather complicate to compare the results obtained from different studies. Therefore, it could be
 568 useful to provide the conversion factors among the units of measurements used to characterize the
 569 evapotranspiration process in green roof.

570 Table 6 summarizes the conversion factors among the units of measurements used to express the
 571 evapotranspiration rate.

572 *Table 6. Conversion factors for evapotranspiration process measurement*

	Depth	Volume per unit area		Energy per unit area	Mass per unit area	Power per unit area
To	mm day^{-1}	$\text{m}^3 \text{ ha}^{-1} \text{ day}^{-1}$	$\text{L m}^{-2} \text{ day}^{-1}$	$\text{MJ m}^{-2} \text{ day}^{-1}$	$\text{kg m}^{-2} \text{ day}^{-1}$	W m^{-2}
From						
mm day^{-1}	1	10	1	2.45	1	28.36
$\text{m}^3 \text{ ha}^{-1} \text{ day}^{-1}$	0.1	1	0.1	0.245	0.1	2.836
$\text{L m}^{-2} \text{ day}^{-1}$	1	10	1	2.45	1	28.36
$\text{MJ m}^{-2} \text{ day}^{-1}$	0.408	4.082	0.408	1	0.408	11.57
$\text{kg m}^{-2} \text{ day}^{-1}$	1	10	1	2.45	1	28.36
W m^{-2}	0.035	0.35	0.035	0.0864	0.035	1

573 *5.2. Evapotranspiration rate carried out by literature studies*

574 Besides providing valuable technical details regarding the methods for measuring ET, experimental set-up
 575 tests also offer useful information on the real quantification of the ET process.

576 Liang Tan et al. (2017) [58] developed a study on both conventional garden soil, which is a commercially
 577 available soil mix commonly used in urban landscapes, and K-soil, which is a proprietary lightweight soilless

578 media, consisting mainly of perlite and organic matter. They found that evapotranspiration ranged between
579 2.0 and 7.0 kg m⁻² d⁻¹. Moreover, the authors also observed that plant evapotranspiration decreased
580 gradually in a similar manner to the corresponding soil water content, to approximately 2.0 kg m⁻² d⁻¹ in both
581 conventional garden soil and K-soil. On the contrary, evapotranspiration was around 4 kg m⁻² d⁻¹ when an
582 artificial soil, consisting mainly of perlite, was tested.

583 Other studies demonstrated that the evapotranspiration for trays with plants was always higher than the
584 evaporation of trays without vegetation [57], especially for trays using periwinkle (leafy plant) than for
585 ryegrass. In the periwinkle test, the water lost by evapotranspiration after 48 hours was 5.2 kg, about twice as
586 much as that lost only by evaporation that was about 3.0 kg. While the water loss was 3.5 kg after 48 hours
587 for the ryegrass sample.

588 A substantial variation of water loss among some plant species was found also in other literature studies. In
589 the tests performed by Schweitzer and Erell (2014) [56], *Aptenia* lost less than half as much water as
590 *Pennisetum*, about 3 L m⁻² day⁻¹ and 7 L m⁻² day⁻¹ respectively. The *Pennisetum* loss rate was even less than
591 in bare moist soil, about 3.8 L m⁻² day⁻¹. Ouldboukhitine et al. (2012) [55] measured that daily
592 evapotranspiration with a grass tray (2.34 mm) was greater than that with a *Sedum* tray (1.42 mm). The
593 cumulative evapotranspiration over three days was around 8.0 mm, 5.0 mm, and 4.0 mm for grass, *Sedum*,
594 and bare soil, respectively. These results are in contrast with those found by Coutts et al. (2013) in [48],
595 where the plants limited the ET. In addition, the daily evapotranspiration measured for grass (2.53 mm) is
596 greater than that calculated by the Penman-Monteith equation (1.66 mm). This difference is probably due to
597 the “tray factor”, as defined by Ouldboukhitine et al. (2012) in [55], and to the input parameters taken in
598 the Penman-Monteith equation such as temperature, aerodynamic resistance, and vapour pressure.

599 Some studies calculated the latent heat flux after measuring the quantity of water lost. In Coutts et al. (2013)
600 [48], the higher latent heat flux on soil (with maximum value about 280 W m⁻²) compared to green roof (with
601 maximum value about 210 W m⁻²) suggested that wet soil freely evaporated while evapotranspiration from
602 the green roof was limited by the lower surface temperatures and water uptake by vegetation. After
603 irrigation, there was a substantial increase in latent heat flux for both green roof and bare soil. Maximum
604 rates of latent heat flux increased on green roof and soil a mean of 100 W m⁻² and 90 W m⁻², respectively.

605 Other studies analysed the relationship between ET and different weather conditions. Jim and Peng (2012)

606 [49] evaluated both different typical days (sunny, cloudy, and rainy) and different substrate water content.
607 The authors found that for a sunny day with moist soil, about 4.0 mm of water is extracted from the substrate
608 to satisfy evapotranspiration (9.3 mm considering 5 mm due to irrigation). The water depletion during a
609 sunny day with dry soil was 13.1 mm and it was notably higher in comparison to a sunny day with moist soil,
610 despite the lower water content in the substrate. On the contrary, a cloudy day with limited solar gains and
611 dry soil notably suffered a subdued depletion, at merely 5.8 mm.

612 Tabares-Velasco and Srebric (2012) concluded in their study [46] that the latent heat flux due to ET reached
613 maximum values during the experiment with high wind speed, around 170 W m^{-2} , while minimum values
614 occurred when there was low solar radiation, around 20 W m^{-2} . Takebayashi and Moriyama (2007) [69]
615 found that the quantity of evaporation from the green surface in November, with maximum value of 0.06 g
616 $\text{m}^{-2} \text{ s}^{-1}$, was higher than in August with maximum value of $0.02 \text{ g m}^{-2} \text{ s}^{-1}$.

617 In the study conducted by Tabares-Velasco and Srebric in (2011) [54], they observed that latent heat rates
618 vary the substrate water content. The green roof sample achieved the largest and nearly constant
619 evapotranspiration rates over 135 Wm^{-2} when VWC was above $0.14 \text{ m}^3 \text{ m}^{-3}$. Evapotranspiration decreased
620 linearly with the VWC up to approximately $0.07 \text{ m}^3 \text{ m}^{-3}$, showing values between 135 and 45 Wm^{-2} .
621 Evapotranspiration rates dropped in a nonlinear way when VWC was lower than $0.07 \text{ m}^3 \text{ m}^{-3}$ with values
622 below 45.0 W m^{-2} . The daily evapotranspiration ratio was about 3.0 when the substrate was wet, with 20.0
623 and 60.0 W m^{-2} latent heat flux during night and day respectively, while the day/night ratio was about 5.0
624 when the substrate is dry, with 50.0 and 150.0 W m^{-2} latent heat flux during night and day, respectively.

625 Since the presented results about evapotranspiration rates make difficult to perform a comparative analysis
626 because of the different units of measurement used by authors, Table 7 shows all data summarized and
627 converted into kg/m^2 to facilitate the cross-comparison of the findings.

628 *Table 7. Summary of the minimum and maximum values obtained from the parameters reviewed in experimental studies*

Reference	Parameter	Description	Minimum value	Maximum value	Units	Climatic conditions	Minimum value $\text{kg m}^{-2} \text{ day}^{-1}$	Maximum value $\text{kg m}^{-2} \text{ day}^{-1}$
[49]	Sky conditions	Sunny day+wet soil	-	9.3	mm	Hong Kong (Cwa)	-	9.3
		Sunny day+moist soil	-	9.0			-	9.0
	Sunny day+dry soil	-	13.1	-			13.1	
	Moisture soil	Cloudy day+wet soil	-	8.1			-	8.1
		Cloudy day+moist soil	-	5.0			-	5.0

		Cloudy day+dry soil	-	5.8			-	5.8
[69]	Season	August	-	0.08	g m^{-2} s^{-1}	Kobe (Cfa)	-	6.9
		November	-	0.02			-	1.72
	Vegetation	Bare soil	-	0.05			-	4.3
		Soil UVA. Solar radiation simulated with UVA lamps for the experiment with a green roof sample without plants.	30	130			1.1	4.6
		Soil Day. Solar radiation simulated with Fluorescent Daylighting VHO lamps for the experiment with green roof sample without plants.	40	100			1.4	3.6
		UVA plants. Solar radiation simulated with UVA lamps for the experiment with a green roof sample with <i>S. spurium</i>	95	115			3.3	4.0
[46,54]	Solar radiation	Base. Solar radiation simulated with Fluorescent Daylighting VHO lamps for the experiment with green roof sample with <i>Delosperma nubigenum</i> .	45	120	W m^{-2}	Pennsylvania (Dfb)	1.6	4.2
	Relative humidity	Humidity. Conditions equal to 'Base' experiment, except that relative humidity was set to 50%.	50	140			1.8	4.9
	Wind speed	Solar. Conditions equal to 'Base' experiment, except solar radiation decreased by 50%.	25	55			0.9	1.9
	Air temperature	Wind. Conditions equal to 'Base' experiment, except wind speed increased to 1 m/s.	40	170			1.4	6.0
		Temperature. Conditions equal to	60	140			2.1	4.9

‘Base’ experiment,
except air temperature
changed to 26 °C.

Base II. Conditions equal
to ‘Base’ experiment in
order to duplicate the
measurements.

			40	150			1.4	5.3
[55]	Vegetation	Sedum	-	5.0		La Rochelle	-	5.0
		Grass	-	8.0	mm	(Cfb)	-	8.0
		Bare soil	-	4.2			-	4.2
[48]	Vegetation	Sedum	20	210		Melbourne	0.7	7.4
		Bare soil	20	280	W m ⁻²	(Cfb)	0.7	9.9
[56]	Vegetation	Soil moist	4.0	6.0			4.0	6.0
		Pennisetum	7.0	9.0			7.0	9.0
		Aptenia	3.0	6.0	L m ⁻² day ⁻¹	Tel Aviv (Csa)	3.0	6.0
		Sesuvium	6.5	7.5			6.5	7.5
		Halimione	7.5	4.0			7.5	4.0
[57]	Vegetation	Periwinkle	0.5	5.0		La Rochelle	0.5	5.0
		Grass	0.5	3.5	kg m ⁻² day ⁻¹	(Cfb)	0.5	3.5
		Soil bare	0.5	3.0			0.5	3.0
[58]	Substrate	Normal soil	2.0	6.0			2.0	6.0
		Artificial soil	2.0	6.0	kg m ⁻² day ⁻¹	Singapore (Af)	2.0	6.0
		Artificial soil + water retention	4.0	7.0			4.0	7.0

629

630 The variability of the results depends on both the instrumentation and the parameters (plant species, substrate
631 type, climatic conditions, etc.) influencing the ET process.

632 In terms of weight, the ET maximum values were 7.0 kg m⁻² day⁻¹ and 3.0 kg m⁻² day⁻¹ respectively, using
633 artificial soil with water retention layer below the substrate and bare soil. In terms of water lost by
634 evapotranspiration, the maximum values during a sunny day were 13.1 mm with dry soil and 8.0 mm using
635 grass. Latent heat flux reached the maximum value with high wind speed conditions (170 W m⁻²) and using
636 bare soil (280 W m⁻²) compared to *Sedum* (210 W m⁻²).

637 Most of the analysed studies performed a comparison between green roof evapotranspiration (plants +
638 substrate) and bare soil evaporation (only substrate). However, few of them evaluated ET when different
639 solutions of green roof layer were alternated and compared, and/or varying the plant species [55–57].
640 Moreover, only Tan et al. (2017) [58] measured evapotranspiration rates varying the substrate type.

641 Few studies evaluated the evapotranspiration under different environmental boundary conditions. In
642 particular, in [49], the weather was differentiated into three types: sunny, cloudy and rainy. Interestingly, Jim
643 and Peng (2012) [49] claim that the dry soil reached $13.1 \text{ kg m}^{-2} \text{ day}^{-1}$ and the wet soil $9.3 \text{ kg m}^{-2} \text{ day}^{-1}$
644 during sunny days. This assumption underlines the importance in evaluating, not only the substrate water
645 content, but also the climatic conditions. Because the limited substrate-moisture effect on ET and associated
646 cooling that could be explained due to sufficient water supply by occasional rainfall events and regular
647 irrigation confined soil moisture variations to a small range during the summer period and to the relatively
648 weak capability of the substrate to hold water tightly during the dry state to resist ET water extraction.
649 This survey has highlighted a lack of studies concerning the effect of the drainage layer on ET. This could be
650 an interesting field for future studies considering that the drainage layer is particularly important since it has
651 the aim of ensuring an optimal balance between air and water within green roof system.
652 Further researches also should focus on optimizing green roof technology with a water retention layer inside
653 the drainage layer in order to increase ET.

654

655 **6. Mathematical models to characterize ET on green roofs**

656 *6.1. Heat and mass transfer models for ET in green roofs*

657 Due to the heat and mass transfer through the roof resulting from shading, insulation, cooling
658 (evapotranspiration) and wind effects, modelling the latent heat flux of green roofs is not a simple process.
659 Many researchers have explored the heat exchange between green roofs and the environment in which the
660 heat and mass transfer in soil were mostly taken as a quasi-steady-state process.

661 The energy exchanged between the green roof surface and the outside environment consists of latent and/or
662 sensible heat. Latent heat is the heat loss by evapotranspiration that involves soil surface evaporation and
663 vegetation transpiration. Evapotranspiration affects the net heat flux by modulating incoming/outgoing heat
664 transfer mechanisms, depending on the plant species and on environmental conditions. An increase in the
665 evapotranspiration rate decreases the convection heat flux related to sensible heat and storage [61]. Several
666 studies obtained numerical results of each heat flux in order to quantify the latent heat flux.

667 Most of the studies used the following equations to evaluate latent heat flux on the plant canopy (L_F) and the

668 soil surface (L_G) [91]:

$$669 \quad L_F = LAI \frac{\rho_a f c_{pa}}{\gamma(r_a + r_{sto})} (q_c - q_{af}) \quad (2)$$

$$670 \quad L_G = \frac{\rho_a f c_{pa}}{\gamma(r_g + r_a)} (q_g - q_{af}) \quad (3)$$

671 Stomatal resistance for transpiration r_{sto} is influenced by factors including solar radiation and vapour pressure
 672 difference, volume water content, temperature of soil. Air resistance for transpiration r_a is associated with
 673 plant height and wind speed [92].

674 The evapotranspiration rate from plant canopy and soil surface can be calculated by the following equations:

$$675 \quad E_c = L_c / \mu \quad (4)$$

$$676 \quad E_g = L_g / \mu \quad (5)$$

677 Feng et al. (2010) [52] simplified heat losses by transpiration (L_c) and evaporation (L_g) in one equation, so
 678 the heat loss by evapotranspiration is given by:

$$679 \quad L_{et} = L_c + L_g = E_{et} \mu \quad (6)$$

680 where, E_{et} is the evapotranspiration rate and is given by $E_{et} = E_c + E_g$. Evapotranspiration rates can be
 681 measured by weighing or by using soil hygrometers, as explained above. This approach was used by
 682 Quezada-Garcia et al. (2017) [93] to develop a heterogeneous model of heat transfer for green roofs.

683 Table 8 summarizes all the references regarding the ET phenomenon within green roofs studies. This table
 684 reports that a heat transfer model for green roofs is based on different approaches and equations to evaluate
 685 the required parameters for the calculation of latent heat flux.

686 *Table 8. Equations and/or models adopted in heat transfer models for green roofs and their validation parameters*

References	Previous equation utilized	Input parameters	Validation parameters
[70]	-	Meteorological data Substrate temperature	Temperature at 2 cm below soil Degree of saturation in substrate
[50]	Rana-Katerji [94]	-	-
[46]	-	Air temperature Air relative humidity Air speed Sky temperature Incoming solar radiation Substrate water content LAI	Evapotranspiration Incident incoming short-wave radiation Incident incoming long-wave radiation Outgoing long-wave radiation Heat fluxes through green roofs Convective heat transfer fluxes Substrate top and bottom layer temperatures

		Substrate temperature	Substrate thermal conductivity
			Plant temperatures
			Average substrate volumetric water contents
			Air velocities
			Room air relative humidity levels and temperatures
			Spectral reflectivity of green roof samples
			Leaf Area Index (LAI)
[93]	Feng et al. [52]	-	Green layer temperature
		Weather data	Soil surface temperature
[59]	Diedjig et al. [70]	Characteristics of vegetation	Temperature at 2 - 8 cm below soil
		Characteristics of soil	
[60]	Banna [95]	-	-
[61]	Levallius [96]	-	-
		Weather data	
[62]	Deardoff [97]	Characteristics of vegetation	Soil surface temperature
		Characteristics of soil	
		Height of plant	
		Minimum stomata resistance	
		Average LAI	
		Soil thermal capacity	Temperature
[76]	Choudhury and Monteith [98]	Soil depth	Moist distribution
	Philip and De Vries [99]	Soil conductivity	Heat flux
		Reflectivity of leaves	
		Soil water conductivity	
		Soil water capacity	

687

688 Most of the developed mathematical models that analyse the energy performance of green roofs were then
689 validated through experimental analysis. Table 8 also shows the principal parameters used to validate the
690 green roof models.

691 Unlike the models presented in section 2, which were developed to evaluate evapotranspiration on bare
692 and/or vegetated soils, the models listed in Table 8 concern green roofs were developed to analyse the energy
693 performance of green roofs. They considered latent heat and not having the ultimate aim of evaluating the
694 phenomenon of evapotranspiration.

695 Among all the models, only Tabares-Velasco and Srebric (2012) [46] measured evapotranspiration in a
696 laboratory set-up to validate the model. Most of the models used soil and/or plant temperatures measured in-

697 situ to validate the proposed models.

698 Some studies, around 35% of the literature reviewed, adopted simplified energy balance models because of
699 the complex structures of green roofs that include canopy and soil. In particular, Tian et al. (2017) [59]
700 analysed the loss of water in the soil through evapotranspiration considering that it occurred only on the
701 surface of soil while He et al. (2016) [53] assumed that the change of soil water content is equal to water loss
702 through evapotranspiration.

703 Hodo-Abalo et al. (2012) [60] developed a model for evaluating the cooling potential of green roofs. The
704 authors solved the heat transfer equations using a finite difference scheme and Thomas algorithm. The
705 authors developed a numerical model based on an implicit finite difference method for discretizing time-
706 average Navier-Stokes equations and for calculating evapotranspiration variations. Evapotranspiration was
707 obtained by summing the hourly values of local latent heat flux from different layers within the canopy,
708 added to the hourly value of soil evaporation.

709 Djedjig et al. (2012) [70] developed a thermo-hydric model considering the thermal inertia of the whole
710 green roof system. This model allowed an explicit calculation of the evapotranspiration, and the thermo-
711 physical properties of the substrate were calculated according to the volumetric water content. The results
712 demonstrate the effectiveness of the explicit calculation of evapotranspiration, unlike the Penman–Monteith
713 equation, which does not incorporate water stress.

714 Tabares-Velasco and Srebric (2012) [46] included a complete validation of heat transfer fluxes, such as
715 evapotranspiration rates. The study had laboratory-rated acquisition equipment for the detailed measurement
716 of evapotranspiration rates by the gravimetric method, while simultaneously measuring the total energy
717 balance on the green roof sample. Thus, the authors used the experimental data to calibrate the green roof
718 evapotranspiration model.

719 The study conducted by Tsang and Jim (2011) [61] modelled a quadratic-like relation between
720 evapotranspiration and the water content in green roofs that allowed an analysis of the latent heat flux of
721 green roofs in terms of volumetric water content in the soil and the relative humidity. This model considers
722 the combined effect of evaporation and transpiration to reduce calculation complexities.

723 He et al. (2017) [76] analysed energy balance of plant and soil layer using a coupled hydro-thermal transfer
724 model validated by field experiments in Shanghai area. In particular, the authors assessed the effects of

725 thickness of soil layer and leaf area index of plant layer on green roof energy and thermal performance. In
726 the model, it was assumed that the water content variation of soil layer equals to the water loss
727 through evapotranspiration.

728 All heat transfer models of green roofs take into account the latent heat flux due to evaporation of water from
729 the substrate and transpiration of plants. However, only a few of them considered experimental data for their
730 validation. Future models should include experimental measurements of ET rates for the validation process.

731 *6.2. Latent heat flux results*

732 This section describes the results found by the studies that used mathematical models to characterize ET on
733 green roofs in order to evaluate the surface energy, focussing on the latent heat flux.

734 Evapotranspiration and net long wave radiation dominate the energy balance of the green roof. In particular,
735 He et al. (2016) [53] found that, under both free-floating and air-conditioned scenarios, the
736 evapotranspiration flux accounted for 58.15% and 63.93% respectively of all the dissipated heat by the green
737 roof. When the moisture content of the soil is low, the proportion of evapotranspiration decreases greatly
738 while heat convection rises. Similar results were obtained by Feng et al. (2010) [52], who found that the heat
739 loss through the evapotranspiration of the plants–soil system accounted for 58.4% of the total energy flux
740 and played the most important role. The net long-wave radiative exchange between the canopy and the
741 atmosphere as sensible heat accounts for 30.9%, and the net photosynthesis of plants accounts for 9.5%.
742 Only 1.2% was stored by plants and soil, or transferred into the room beneath. During the day, Tian et al.
743 (2017) [59] found that most of the absorbed radiation (about 40%) is dissipated as latent heat on the canopy.
744 However, other studies found controversial results regarding the role of evapotranspiration in the green roof
745 energy balance. Schweitzer and Erell (2014) [56] estimated that the contribution of evaporation was the least
746 important of these mechanisms (about 4%). In addition, Coutts et al. (2013) [48], through an experimental
747 analysis, evaluated the surface energy balance for green roof and bare soil, showing that only a small portion
748 of the overall heat flux was partitioned into latent heat (0.15%) for green roof and for bare soil (0.13%).
749 These results show that when succulent vegetation with coverage less than 100% and in absence of irrigation
750 the evapotranspiration achieves modest benefits. The mean daytime evaporative fraction is strictly connected
751 with the time of irrigation. It increased about 41% for green roof and 51% for bare soil immediately after the

752 irrigation, while by the third day of having watered the latent heat flux was reduced by 26% in the green roof
 753 and by 38 % in the bare soil.

754 The study conducted by Lazzarin et al. in 2005 [50] evaluated the performance of a green roof system in
 755 summer in both dry and wet conditions. The wet soil gave rise to an evapotranspiration rate of about 25.0%
 756 of the overall heat flux, whereas in dry conditions that contribution was limited to 12.0%.

757 Tsang and Jim (2011) [61] observed that the peaks of latent heat flux (about 7 Wm^{-2}) were achieved when
 758 long period of high solar radiation occurred. Thus, solar radiation could expedite the evapotranspiration rate
 759 and increase the latent heat loss.

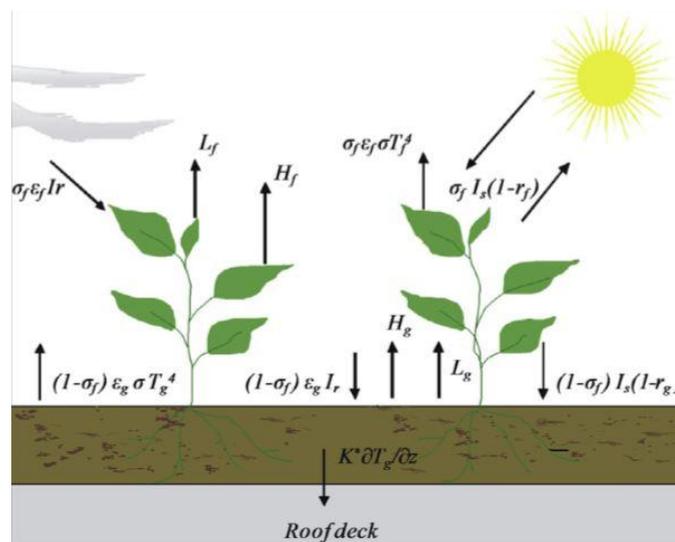
760 These results show the importance of evapotranspiration in reducing thermal loads in a green roof. As a
 761 general outcome of this section, it is possible to observe that the latent heat flux calculated through
 762 mathematical models showed a wide range of values on the overall heat flux in a green roof, depending on
 763 the mathematical model used and the boundary conditions assumed (climatic conditions).

764

765 7. Evaluation of ET through dynamic simulation

766 7.1. EnergyPlus software

767 This section shows the ET results obtained by using EnergyPlus [63–65] dynamic simulation software.



768

769

Figure 5. Energy balance of a green roof [17]

770 EnergyPlus integrates a green roof model developed by Sailor (2008) [100] and based on an Army Corps of
 771 Engineers' FASST vegetation model [101]. This model considers simultaneously the foliage surface and soil

772 temperatures at each time step. The “Ecoroof” module is a one-dimensional model containing energy
 773 budgets for both the foliage layer and the soil surface. It considers long and short wavelength radiation
 774 exchanges, the effects of vegetation on convective (sensible heat) thermal flux, evapotranspiration (latent
 775 heat), heat storage and transfer through the substrate (Figure 5).

776 The energy balance for the foliage is the following (Eq. 1):

$$777 \quad F_f = \sigma_f [I_s(1 - \alpha_f) + \varepsilon_f I_{ir} - \varepsilon_f \sigma T_f^4] + \frac{\sigma_f \varepsilon_f \varepsilon_g \sigma}{\varepsilon_1} (T_g^4 - T_f^4) + H_f + L_f \quad (9)$$

778 where $[I_s(1 - \alpha_f) + \varepsilon_f \sigma T_f^4]$, $\frac{\sigma_f \varepsilon_f \varepsilon_g \sigma}{\varepsilon_1} (T_g^4 - T_f^4)$, H_f and L_f are shortwave solar radiation, long wave
 779 radiation exchange between sky and foliage, convective heat transfer between air and foliage as sensible heat
 780 flux, and evapotranspiration on the foliage surface as latent heat flux, respectively.

781 The energy balance for the soil surface is the following (Eq. 2):

$$782 \quad F_g = (1 - \sigma_f) [I_s(1 - \alpha_g) + \varepsilon_g I_{ir} - \varepsilon_g T_g^4] - \frac{\sigma_f \varepsilon_f \varepsilon_g \sigma}{\varepsilon_1} (T_g^4 - T_f^4) + H_g + L_g + k \times \frac{\delta T_g}{\delta z} \quad (10)$$

783 where all the terms have the same meaning as in Equation (1), but are referred to the soil layer. The last term
 784 represents the conductive heat transfer in the soil substrate.

785 The “Ecoroof” module allows to specify various features of the green roof, including height of plants, leaf
 786 area index (LAI), leaf reflectivity, thickness/density/thermal conductivity and specific heat of soil.

787 Table 9 provides input data for the green roof model in EnergyPlus reported by Peri et al. (2016) [79].

788 However, many previous studies assuming theoretical data for the features of substrate and plant species
 789 have already been developed. Therefore, the thermo-physical values used in the simulations not always may
 790 be confirmed through experimental test. As rule, it is necessary to use only realistic thermo-physical values,
 791 which have to be associated with specific plant and substrate types.

792 *Table 9 Range of values provided by Peri et al. (2016) [79] for an EnergyPlus model*

Input Parameter	Range of values	
	Minimum	Maximum
LAI	0.1	5
σ_f	0	1
Canopy albedo	0.1	0.4
ρ_g	0.04	0.4
k_l	0.3	0.83
σ_t	0.11	0.5
τ_t	0.2	0.2

794 Boafo et al. (2017) [63] investigated the potential contribution of the evapotranspiration in green roofs on the
795 annual energy consumption of an office building located in Incheon, Republic of Korea. So this study could
796 be representative of the Dwa climate according with the Köppen classification (2006) [102]. The
797 evapotranspiration flux was evaluated varying the LAI (from 1 to 5) as well the irrigation regime. They
798 found that the average monthly evapotranspiration ranged from 1.80 mm·day⁻¹ to 4.79 mm·day⁻¹ for high
799 LAI, from 0.31 mm·day⁻¹ to 4.16 mm·day⁻¹ for low LAI from 1.31 mm·day⁻¹ to 4.28 mm·day⁻¹ for high
800 irrigation. For the scenarios without irrigation the ET varied from 1.31 mm · day⁻¹ to 3.92 ·mm day⁻¹, in
801 December and May respectively. As expected, the highest and lowest evapotranspiration fluxes were found
802 during summer and winter, respectively. The latent heat flux, associated to the evapotranspiration, increasing
803 the LAI from 1.0 to 5.0, was grown-up by 10.4% in summer and 80.2% in winter keeping soil thickness
804 constant. Silva et al. (2016) [64] analysed the thermal performance of intensive and extensive green roofs
805 located in Lisbon, Csa climate according to the Köoppen classification. The evapotranspiration was
806 significantly different in extensive green roofs (max value 2 mm·day⁻¹·10⁻⁴) when compared to semi-
807 intensive (max value 6 mm·day⁻¹·10⁻⁴) and intensive roofs (max value 9 mm·day⁻¹·10⁻⁴), particularly in
808 summer when the solar radiation was higher. Vera et al. (2017) [65] investigated the effect of the variation of
809 the LAI of the green applied over an uninsulated concrete slab and lightweight metal roofs, in different
810 climate, i.e. Bsk (Albuquerque), Csc (Santiago) and Cfb (Melbourne) according to the Köppen classification.
811 In this study, the LAI values were varied between 0.1 and 5.0 that represent the range of potential values for
812 vegetated roofs. The results show that the cooling load of the room decreases when LAI increases because of
813 the increase in the evapotranspiration that diverts incoming solar heat gains through the roof, for the three
814 evaluated cities. A heat flux reduction of about 20.0 W/m² was calculated when a vegetated roof without
815 plant was compared to a vegetated roof with plants having a LAI equal to 5.0. Finally, the highest
816 evapotranspiration flux was achieved with a LAI of 4.79 mm·day⁻¹) and irrigation of 4.28 mm·day⁻¹ during
817 the summer period.

819 **8. Sensitivity analysis of green roof ET**

820 The above performed review have highlighted that there is a plethora of parameters, as well as their
821 reciprocal meddling, that affect the evapotranspiration process. Thereby, several studies from the literature
822 review have tried to perform sensitivity analysis to understand which parameter most affects ET.

823 Tsang and Jim (2011) [61] have investigated the influence of the volumetric water content and the air
824 convection coefficient on the performance of the green roofs. Their sensitivity test showed that an increase
825 from 30 to 60 % of VWC implies a reduction of heat stored in the green roofs by 24 %. While, the increase
826 from 12 to 16 $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ of the convection coefficient reduces the heat stored by 45 %.

827 Tabares-Velasco and Srebric (2012) [46] carried out a sensitivity analysis of the energy performance of the
828 green roof, considering the effect of soil thickness, wind velocity, volumetric water content, solar radiation,
829 and stomatal resistance. The results of this study provide, in function of the parameters and their range of
830 variation analysed, the evapotranspiration rate expressed as latent heat flux. Starting from these results,
831 Figure 6 has been developed in this review study with the aim to synthetize and systemize the reading of the
832 performed study by Tabares-Velasco and Srebric (2012).

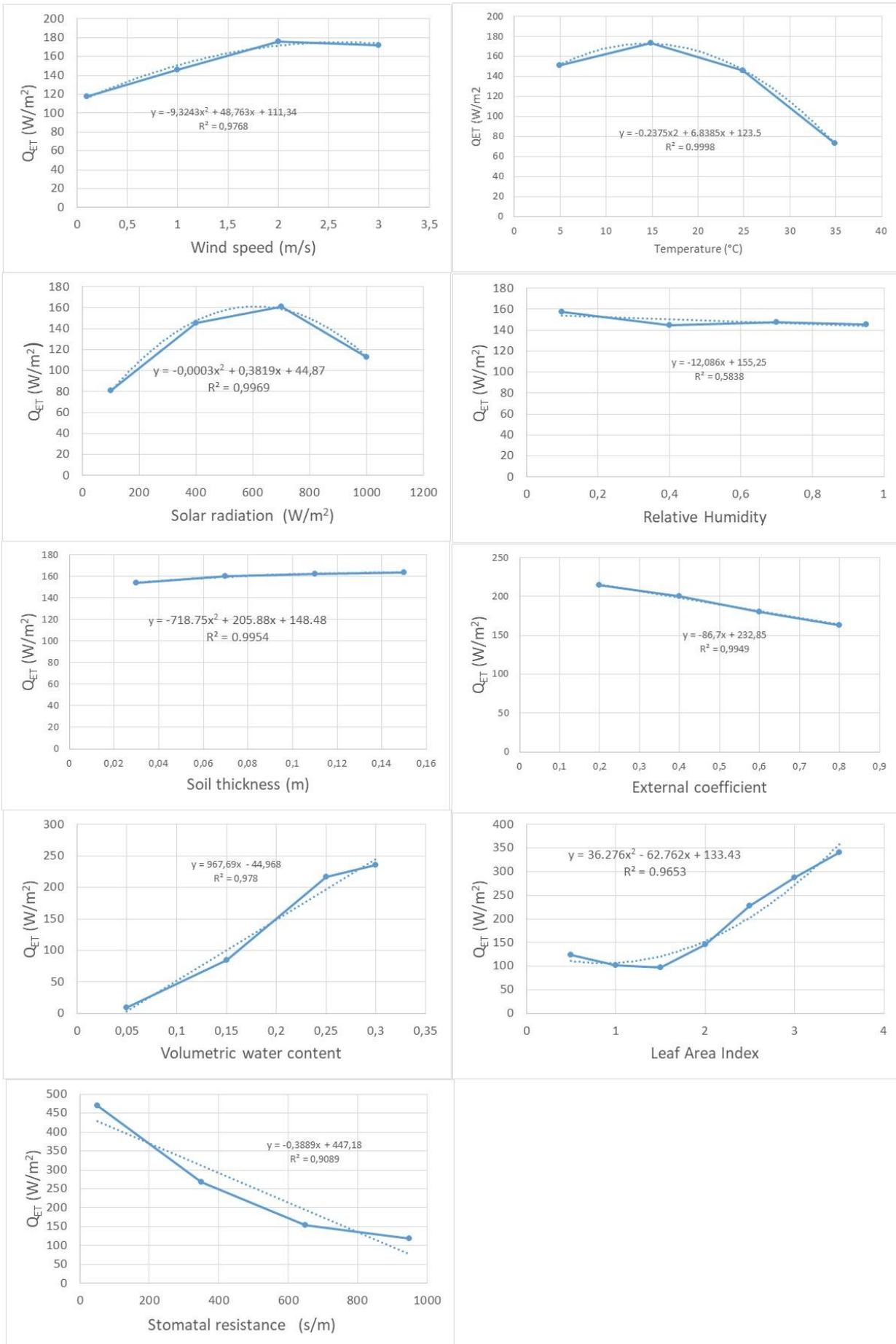


Figure 6. ET Sensitivity analyses

835 This sensitivity analysis highlighted that the highest values of evapotranspiration were obtained with high
836 volumetric water content in the substrate (0.25 and 0.30), reduced stomatal resistance (50 and 350 s/m), high
837 values of LAI (2.5, 3.0 and 3.5), and with low values of external coefficient, i.e. incoming long and short
838 wave radiation, (0.2 and 0.4). Where the radiation emitted from earth/atmosphere is terrestrial or longwave
839 radiation and the radiation emitted from sun is solar or shortwave radiation. These results can be inferred by
840 observing the value assumed for the different percentage between the minimum and maximum values of ET
841 (ΔQ_{ET}). The volumetric water content is the variable with the largest difference ($\Delta Q_{ET}=96.3\%$) between the
842 minimum and maximum value of evapotranspiration, from 8.8 to 235 W/m².

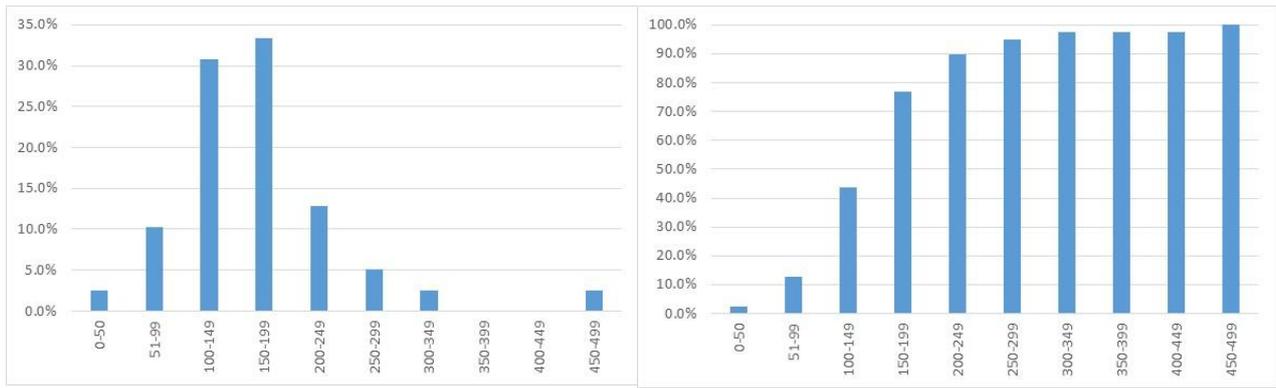
843 Stomatal resistance and LAI also produce considerable variations in the ET, with values between 469.5 and
844 118.5 W/m² ($\Delta Q_{ET}=74.8\%$) and between 340.6 and 97.4 W/m², ($\Delta Q_{ET}=71.4\%$), respectively.

845 In a similar manner, the variables with less influence on evapotranspiration process were identified. When
846 substrate thickness and relative humidity vary, the evapotranspiration flux remains almost constant, with a
847 ΔQ_{ET} variation of 5.8 and 7.8 %, respectively. Values of evapotranspiration lower than 145 W·m⁻² are never
848 reached whatever was the variations in relative humidity, substrate thickness, and long and short wave
849 radiation.

850 Furthermore, Figure 6 shows that wind speed, volumetric water content, and leaf area index have a positive
851 correlation with ET, i.e. the higher these values, the higher the ET. Otherwise, air temperature, external
852 coefficients (long and short wave radiation), and stomatal resistance are characterized by a negative
853 correlation with ET. Finally, relative humidity and soil thickness present a neutral correlation.

854 The performed elaboration allows to evidence as all the parameter variations can be represented by means of
855 a second order polynomial regression, which shows rather high value of the correlation coefficient R².
856 Therefore, this correlation could constitute a reference for comparing set of experimental results coming
857 from different studies.

858 Moreover, a frequency analysis on the results coming from Tabares-Velasco and Srebric (2012) [62] was
859 also carried out. It is possible to observe that the highest frequencies of Q_{ET} are in the range 100-149 and
860 150-199 Wm⁻² (Figure 7, left). The cumulative curve (Figure 7, right) indicates that 90% of the values of Q_{ET}
861 are lower than 249 Wm⁻².



862
863 *Figure 7. A frequency analysis of energy for evapotranspiration Q_{ET} (left) and the cumulative curve (right)*

864 This section has highlighted which factors are influencing ET and how their variation has positively or
865 negatively affect evapotranspiration. Moreover, after having analysed data from the literature the
866 correlations, as well as the range of variation of ET found, helps in establishing a comparative framework
867 between different researches.

868

869 9. Conclusions

870 The purpose of this study was to review the impact of ET on green roofs. Although most of the studies agree
871 to consider evapotranspiration among the main factors affecting the behaviour of green roofs, only few
872 studies experimentally assessed evapotranspiration rates. The following general conclusions can be drawn:

- 873 - The experimental studies carried out have made use a wide variety of equipment and techniques for
874 the measurement of ET. When the objective is directly to assess the evapotranspiration of green
875 roofs, high precision load cells that determine the evolution of weight over time are the most widely
876 used equipment.
- 877 - Many of the mathematical models used to evaluate the performance of green roofs take into account
878 the latent heat flux due to evaporation of water from the substrate and transpiration of plants.
879 However, only few models were validated considering experimental data of evapotranspiration rates,
880 and in many cases, the experiments were conducted in laboratory conditions and for short periods.
881 Therefore, more research that experimentally analyses all factors that affect the ET phenomenon
882 under real conditions will help to fill the gap in the current state of the art.
- 883 - The high variability of technical-constructive solutions and climatic conditions affecting the energy
884 performance of green roofs, the different units of measurement used to quantify evapotranspiration,

885 the lack of information regarding the duration of the experiments, and the specific climatic
886 conditions make it difficult to compare the results obtained from different studies. Thus, some
887 guidelines to develop a correct experimental methodology could help in providing better
888 comparative analysis for future research.

- 889 - Some studies evaluated evapotranspiration in green roofs by comparing roofs with and without
890 vegetation and by implementing different plant species. However, only few of them evaluated the
891 evapotranspiration rate by varying the type of substrate. Finally, an important lack of studies
892 considering the role of the drainage layer in the ET process of a green roof was also detected.
- 893 - There are geographic areas of the world with high potential ET rates where this phenomenon has not
894 yet sufficiently evaluated for green roofs.
- 895 - There are no studies correlating ET with external surface temperatures of the green roof, although
896 many studies determined that one of the main advantages of using green roofs is the reduction of
897 surface temperatures and the consequent mitigation of the urban heat island effect.

898 Furthermore, the following are the specific conclusions:

- 899 - Load cells are the equipment that could be recommended for future studies to assess the
900 evapotranspiration of green roofs in a direct and high precision way. They allow monitoring the
901 evolution of the tray weights due to water loss over time in $\text{kg m}^{-2} \text{day}^{-1}$ that is the most appropriate
902 unit of measurements to estimate the evapotranspiration at any desired time-step.
- 903 - The sensitivity analysis highlighted that the highest values of evapotranspiration were achieved with
904 high volumetric water content in the substrate, reduced stomatal resistance and high values of LAI.
- 905 - On one hand, the variation of the volumetric water content in the substrate causes the largest
906 fluctuation between the minimum and maximum values of evapotranspiration. On the other hand,
907 the variation in the substrate thickness and relative humidity showed the minimum variation on the
908 heat flux, being the parameters that less affect the ET in a green roof.
- 909 - Here the importance of testing experimentally the ET process during enough extended periods of
910 time, covering all the different seasons and climate conditions to correlate the ET with the main
911 meteorological scenarios (e.g. sunny, cloudy, and rainy days) have to be highlighted.

912 - Moreover, further studies should be carried out to assess the evapotranspiration of different green
913 roof solutions considering the influence of the drainage, as well as to investigate those geographic
914 areas of the world, which has high potential for green roof evapotranspiration.

915 Globally, this review analysis provides valuable information for building companies, architects, engineers,
916 designers and stakeholders, on the ET of various green roof solutions and the different materials used. In
917 addition, this paper highlighted the principal gaps in the current literature that will lead researchers to
918 perform new studies within this topic.

919

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928

929 **Nomenclature**

930	C_d	Denominator constant that changes with reference type and calculation time step, s/m
931	C_n	Numerator constant that changes with reference type and calculation time step, $K \text{ mm s}^3 \text{ M/g/d}$ or K
932		$\text{mm s}^3 \text{ M/g/h}$
933	C_{pa}	Specific heat of air at constant pressure, $\text{J/kg}^\circ\text{C}$
934	e_a	Actual vapour pressure, kPa
935	e_s	Saturation vapour pressure
936	E_g	Evaporation rate on soil surface, $\text{kg/m}^2/\text{s}$
937	E_c	Transpiration rate on plant canopy, $\text{kg/m}^2/\text{s}$
938	E_{et}	Evapotranspiration rate, $\text{kg/m}^2/\text{s}$
939	ET	Evapotranspiration rate, mm/h
940	ET_0	Reference evapotranspiration rate from a grass surface, mm/h
941	ET_{sz}	Reference evapotranspiration rate from a standardized surface, mm/h
942	F	Net heat flux, W/m^2
943	G	Soil heat flux, W/m^2
944	H	Sensible heat flux, W/m^2
945	K	Dry soil thermal conductivity W/m/K
946	I_{ir}	Total incoming long wave radiation, W/m^2
947	I_s	Total incoming short wave radiation, W/m^2
948	L	Latent heat flux, W/m^2
949	L_c	Latent heat flux on plant canopy, W/m^2
950	L_g	Latent heat flux on soil surface, W/m^2
951	L_{et}	Latent heat flux from evapotranspiration, W/m^2
952	LAI	Leaf area index, -
953	PET	Potential ET rate, mm/h
954	q_{af}	Vapour pressure of the air within plant canopy, Pa
955	q_c	Vapour pressure of the air in contact with plants, Pa
956	q_g	Vapour pressure of the air in contact with soil, Pa

957	Q_{ad}	Energy transported by evapotranspired water, W/m^2
958	Q_a	Sensible heat flux to the air, W/m^2
959	Q_s	Heat flux to the soil, W/m^2
960	Q_c	Heat storage in the crop, W/m^2
961	Q_p	Energy available for photosynthesis, W/m^2
962	R_n	Net solar irradiance, W/m^2
963	R_s	Incoming solar irradiation, $MJ/m^2/d$ or $MJ/m^2/h$
964	r_a	Aerodynamic resistance to transpiration, s/m
965	r_{sto}	Stomatal resistance to vapour diffusion, s/m
966	r_g	Aerodynamic resistance to evaporation on soil surface, s/m
967	T	Temperature, K
968	T_a	Mean monthly/daily/hourly air temperature, $^{\circ}C$
969	TD	Mean maximum minus mean minimum temperature, $^{\circ}C/day$
970	T_F	Mean monthly/daily/hourly air temperature, $^{\circ}F$
971	u_2	Wind speed at 2m height, m/s
972	z	Height or depth, m
973	<i>Greek letters</i>	
974	α	Albedo, -
975	Δ	Slope of saturation vapour pressure with air temperature, $kPa/^{\circ}C$
976	ε	Thermal emissivity, -
977	ε_1	View factor, -
978	γ	Thermodynamic psychometric constant, kPa/K
979	ρ_a	Air density, kg/m^3
980	ρ_{af}	Density of air within plant canopy, kg/m^3
981	λ	Latent heat of evaporation, MJ/kg
982	μ	Latent heat of vaporization of water, J/kg
983	σ	Stefan-Boltzmann constant, $W m^{-2} K^{-4}$
984	σ_f	Fractional vegetation coverage, -

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