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State-of-the-art analysis of the environmental benefits of green roofs

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HIGHLIGHTS

- Cross-disciplinary review is performed for showing benefits of green roofs.
- Green roofs have several benefits for energy, water and pollution management.
- Experiments show that green roofs must consider specific climatic conditions.
- Lifecycle analysis ensures the economic feasibility of green roofs.
- Quantification of the green roof performances needs to consider technical design.

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ABSTRACT

Green roofs have been proposed for sustainable buildings in many countries with different climatic conditions. A state-of-the-art review of green roofs emphasizing current implementations, technologies, and benefits is presented in this paper. Technical and construction aspects of green roofs are used to classify different systems. Environmental benefits are then discussed mainly by examining measured performances. By reviewing the benefits related to the reduction of building energy consumption, mitigation of urban heat island effect, improvement of air pollution, water management, increase of sound insulation, and ecological preservation, this paper shows how green roofs may contribute to more sustainable buildings and cities. However, an efficient integration of green roofs needs to take into account both the specific climatic conditions and the characteristics of the buildings. Economic considerations related to the life-cycle cost of green roofs are presented together with policies promoting green roofs worldwide. Findings indicate the undeniable environmental benefits of green roofs and their economic feasibility. Likewise, new policies for promoting green roofs show the necessity for incentivizing programs. Future research lines are recommended and the necessity of cross-disciplinary studies is stressed.

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Nomenclature

$C_{e,g}$	latent heat flux bulk transfer coefficient at ground layer
C_f	bulk heat transfer coefficient
C_{hg}	sensible heat flux bulk transfer coefficient at ground layer
$C_{p,a}$	specific heat of air at constant pressure
F_f	net heat flux to foliage layer (W/m^2)
F_g	net heat flux to ground surface (W/m^2)
h	effective heat transfer coefficient with convection + radiation
h_{fg}	latent heat of evaporation
H_f	foliage sensible heat flux (W/m^2)
H_g	ground sensible heat flux (W/m^2)
$I_s^{\downarrow}$	total incoming short-wave radiation (W/m^2)
$I_{ir}^{\downarrow}$	total incoming long-wave radiation (W/m^2)
l_f	latent heat of vaporization at foliage temperature (J/kg)
l_g	latent heat of vaporization at ground temperature (J/kg)
K	total thermal conductivity
L	characteristic depth of green roof
L_f	foliage latent heat flux (W/m^2)
L_g	ground latent heat flux (W/m^2)
LAI	leaf area index (m^2/m^2)
m	evaporation flow rate
q_{af}	mixing ratio for air within foliage canopy
$q_{f,sat}$	saturation mixing ratio at foliage temperature
$q_{g,sat}$	saturation mixing ratio at ground temperature
Q_{cond}	conduction heat
Q_{irr}	radiation heat
Q_{conv}	convection heat
Q_{evap}	evapotranspiration heat
r''	surface wetness factor
T_{af}	air temperature with in the canopy
T_f	foliage temperature
T_g	ground surface temperature
T_C	temperature of cold space
T_S	temperature of green roof surface
T_∞	ambient temperature
V_∞	air velocity
W_{af}	wind speed within the canopy
α_f	albedo (short-wave reflectivity) of the canopy
α_g	albedo (short-wave reflectivity) of ground surface
ε_f	emissivity of canopy
ε_g	emissivity of the ground surface
ε_1	$\varepsilon_g + \varepsilon_f - \varepsilon_g \cdot \varepsilon_f$
φ_∞	relative air humidity
ρ_{af}	density of air at foliage temperature
ρ_{ag}	density of air at ground surface temperature
θ	moisture content
σ	Stefan–Boltzmann constant
σ_f	fractional vegetation coverage

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1. Introduction

It is repeatedly documented that approximately 40% of worldwide energy use is associated with the construction and maintenance of buildings [1–3]. Buildings are also responsible of the 33% of greenhouse gas emission globally. Due to the high rate of energy and resource consumption of buildings, various sustainable approaches and environmentally responsive energy efficient technologies have been proposed and implemented to realize low-energy buildings [2,3]. These include advanced eco-technologies, energy efficient systems and renewable energy sources. In this context, green roofs are often identified as a valuable strategy for making buildings more sustainable [3–5].

Green roofs are also named "eco-roofs", "living roofs" or "roof gardens", and are basically roofs with plants in their final layer [5,6]. Green roofs are generally built to enhance the energy efficiency of their buildings, but many other benefits exist. In fact, their vegetation layer realizes photosynthesis processes whereas their soil layer allows absorption of rainfall, often resulting in an improvement in water runoff quality [7].

This paper targets to develop a state-of-the-art analysis of environmental benefits of green roofs to help understanding their status, new trends, and potentials. Furthermore, it aims to identify multi-disciplinary insights for environmental benefits of green roofs. These have often been indicated as complex systems, which require collaborative efforts by architects, engineers, horticulturists, contractors, and urban planners [5,6]. The advantages of green roofs have determined the attention of different disciplines, with the result that research related to them is dispersed among many different journals in different fields [8]. By using a multi-disciplinary approach, this paper claims that the benefits and impacts of green roofs are highly interrelated with the goals of sustainable buildings [9]. Only papers published in the last ten years will be considered, with a higher attention to papers appeared after 2008.

The following section presents an overview of current interpretations and classifications of green roofs. Section three focuses on technical aspects and structure of green roofs. In section four, environmental benefits of green roofs, including energy reduction for cooling/heating purposes, urban heat island mitigation, air pollution reduction, rainwater management, noise reduction, and ecological preservation are discussed. Section five focuses on the economic feasibility of green roofs and on policies incentivizing their implementation. The study concludes by showing future directions of research, stressing the identified critical points and the respective solutions, and the ultimate potential of green roofs for promoting sustainability.

2. An overview of literature on green roofs

2.1. Background

Existing literature shows that several types of green roofs have been used in different countries for centuries with confirmed