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A Conceptual Review of the Potential of Cool Roofs as an Effective Passive Solar Technique: Elaboration of Benefits and Drawbacks

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Cool roofs, as feasible and efficient passive solar technique that reduces building energy requirements for cooling and improves indoor thermal comfort conditions, have received considerable attention in recent years and as a result, a number of concepts, methods, and experiences have been developed during the related research. Although some studies have been conducted on this subject in the form of review articles, taking into consideration the large number of publications, there is still a call for some review papers dealing with the potential of cool roofs and providing a thorough report on their energy performance and a detailed summary of their pros and cons on the basis of the relevant studies. On this account, this study contributes a systematic review of the issued paper in Scopus and Web of Science regarding the cool roof technologies to recognize the advantages and challenges of cool roofs in practice and its future trends. In addition, detailed summary of advantages and drawbacks of this passive solar measure has been developed, as itemized factors corresponded to the codified references. A total of 90 published reports were analyzed, declaring that a cool roof is an efficient approach for generating clean energy on the building scale. This article induces an overall view of the advantages and restrictions of the cool roof throughout the world. Conclusions give a valuable reference for improving the cool roof design for their more widespread use in the building industry.

Keywords: passive solar technique, solar energy, cool roof, energy efficiency, thermal performance

1 INTRODUCTION

Environmental crises such as global warming, ozone depletion, air pollution and water pollution, along with a shortage of energy resources, are two main problems for today's world (Abdul Mujeebu and Alshamrani, 2016; Shafique and Kim, 2017). There is no question that all of these issues resulted from the excessive use of fossil fuels, which have accounted for a large part of the global energy demand in recent decades. Other than the harmful environmental effects and the huge cost of fossil fuel resources, it is obvious that they are non-renewable and will inevitably end at some point, perhaps in the near future. Accordingly, one of the most important challenges facing scientists and experts today is to find an acceptable alternative to fossil fuels that have as little adverse environmental impact as possible and are also renewable (Rosenfeld et al., 1998).

They, therefore, pursued more eco-friendly energy resources, such as solar energy, wind power, hydropower, and geothermal energy, and explored to establish an effective, sustainable mechanism for the utilization of these supplies (Kannan and Vakeesan, 2016). Solar energy can be regarded the best option in this respect because it is the most accessible source of renewable sources of energy, i.e. many areas of the globe enjoy an adequate amount of solar radiation, and it is also not exhaustible. Greenhouse gases are one of the main givers to global warming, and the building sector considers for a great part of total global energy depletion and Greenhouse gases emission (Imran et al., 2018). There have been several strategies to diminish greenhouse gasses emissions in the building system, including generating energy onsite in a further effective and sustainable practice, decreasing energy depletion, and using power more efficiently. Various researchers have inscribed several sustainable techniques and strategies for building roofs to develop the energy performance in buildings. Some of these techniques are old, while others have only been introduced in the former few years. Many analyses, simulations, and case studies can be seen in this field (Marrana et al., 2017; Ashraf et al., 2018; Pradhan et al., 2019). Several experimental and modeling investigations have been written that analyze building energy performance benefits of cool roofing methods (Santamouris et al., 2011; Akbari and Kolokotsa, 2016; Pisello, 2017; Jeong et al., 2021; Macintyre et al., 2021). Few studies focus on analyzing the advantages and disadvantages of different methods of the cool roof in various climate conditions. (Testa and Krarti, 2017; Hu and Yu, 2019; Rawat and Singh, 2021a).

Moreover, as expected, the need for energy resources will increase in the years to come as a result of population growth and technological progress (Lotfabadi, 2015). High-energy use will additionally lead to environmental depravity and append the influence on climate change situations. High energy consumption is more considerable in tropical and semitropical regions than others, principally for meeting the requirement for cooling. Energy-conscious designs and methods reduce the cooling loads to minimize buildings' structure and operational costs (Frontini et al., 2012; Yeganeh and Kamalizadeh, 2018; Yeganeh, 2020; Norouzi et al., 2021). The Roofs of the building reaching inside form the environment in hot-dry, warm, and humid, and composite climatic zones provide approximately 50–60% load in an entire cooling load. Cooling is a crucial demand of the building, particularly in these altitudes. The roof is a principal part of the building cover exposed to solar radiation and provides the highest load of the total cooling load of the building (Cheikh and Bouchair, 2008). To provide a comprehensive review of the cool roof benefits and challenges, this review research strives to recognize the recent improvements on cool roofs worldwide. In addition, this article will help researchers attain a form of information from which they can convey the subsequent level of study on cool roofs and assist directorial and general practitioners in using cool roofs more broadly in future smart cities.

The purpose and objective of this literature review for the application **of Cool Roofs as an Effective Passive Solar Technique** are summarized as:

- Various types and configurations of cool roofs, as well as a thorough report on their energy efficiency
- Many general advantages and drawbacks of passive solar application concerning energy utilization were also synthesized.
- Collecting relevant publications in the last 2 decades.
- Further development of cool roof technology performs.

2 METHODOLOGY FOR BACKGROUND SEARCHING

This literature research presents a significant review of the state-of-the-art study into cool roofs. This part regards the research steps related to making this well-organized analysis of the report. An accurate and comprehensive literature review can give valuable data regarding the basic information of cool roof uses in sustainable building design and show future study trends. The subsequent principal steps were exerted for the literature finding.

2.1 Introductory Research

This step involves the introductory research in the Springer and Direct Science gateways. The best journals containing the "cool roofs" keyword in the title and keywords were picked in this research. The keywords linked to the above topic were also studied, and the associated data was derived from numerous journals.

2.2 Content Collection Classification

A four-step research method (**Figure 1**) was applied to obtain the essays for this review. First, two major scientific databases, Thomson Reuters Web of Science and Scopus, were recognized for the keywords exploration. Next, a combination of keywords and phrases was selected based on the study group's open scientific data and information. Multiple keywords were chosen in English, including passive solar design-cool roof, cool roof, a building envelop, cool materials.

2.3 Concluding Election of Papers

Afterward, a manual screening method was given out based on the titles, abstracts, titles, and keywords. The center of this research was peer-reviewed journal articles, conference articles.

Lastly, in the fourth step, after studying the complete texts of the resting articles, 90 articles directly and indirectly related to the topic were selected for a thorough review investigation.

The principal objective of this study is to give complete knowledge about the cool roof. This article also explains the challenges that require consideration before applying cool roofs on a large scale. The research recommends the possible pathways for utilizing green energy through the synergy of several renewable energy methods on the building scale to improve power production from the cool roofs and present eco-friendly management gains.

3 PASSIVE SOLAR DESIGN

There are basically two main approaches for utilizing solar energy in buildings, i.e. using active systems and passive systems. Active

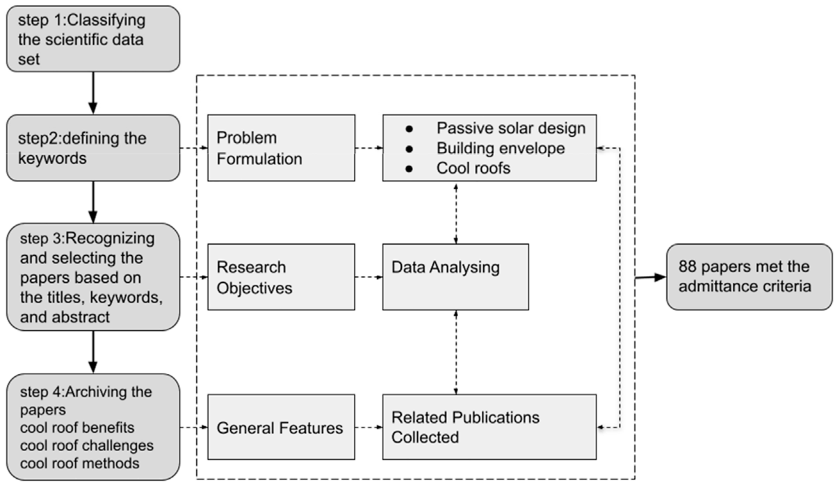

FIGURE 1 | The overall research process.

systems employ mechanical and electrical equipment such as photovoltaic panels, collectors, voltage regulators, blowers, and pumps to absorb and convert the Sun's radiation, while passive systems deal with the application of certain considerations in the design of buildings that leverage the capacity of the local environment yet at the same time minimizing the negative effects of the climate on the comfort level of the building (Rawat and Singh, 2021b). Since this paper focuses on the subject of cool roofs dealing with passive solar measures, the topic of active systems is beyond the scope of this study and will not be addressed any further.

It would, however, be worth tackling passive solar measures a little further. Historically, before the development of mechanical heating and cooling, the solar passive building design strategies were employed for thousands of years, by requirement, and it has remained an integral part of vernacular architecture in many countries (Singh et al., 2011). The passive design strategies can be defined as the use of solar energy, along with the characteristics of local climate and building materials, in order to directly sustain thermally favorable conditions in the built-up environment while mitigating energy consumption (Rabah, 2005). At the conceptual design stage, the biggest possibilities for incorporating passive solar design strategies arise by deciding the values of parameters that have a vital effect on building performance, such as building form, opaque envelope elements, glazing, and shading, etc. In this approach, attempts are being made to integrate certain methods into the design of various parts of the house, such as its outer envelope including the roof and walls, so as to enable the best possible use of solar energy (Bilgiç, 2003; Yeganeh, 2017).

Passive solar architecture techniques offer efficient ways to utilize solar energy without the use of electrical or mechanical devices to help create thermal comfort in buildings. The flow of energy in passive design is achieved by natural means: radiation, conduction, or convection without using any electrical device (Al-Obaidi et al., 2014). The passive techniques have the potential to be utilized for both heating and cooling. The heating systems shall supply or collect and store the solar heat and maintain the heat inside the house. In comparison, cooling systems are intended to provide the building with cold or protection from direct solar radiation and improve air ventilation (Kamal, 2012).

3.1 Importance of Cool Roofs as an Efficient Passive Technique

Passive solar techniques, as has been described, are the most feasible measures that can be put into practice for the proper utilization of solar energy and thus for the enhancement of the thermal performance of buildings. However, these measures are often related to some features in the design of the building envelope. The building envelope is mainly designed to limit the heat transfer between the inside and the outside in order to control the thermal characteristics of the interior environment and to reduce the need for heating, cooling, and electrical lighting in buildings (Azari, 2014; Yeganeh, 2015; Yeganeh et al., 2018; Motevallian and Yeganeh, 2020). Thus, as Silva et al. (2016) maintained, the energy efficiency of buildings strongly depends on the thermal performance of their envelope.

Basically, Cool roofs or solar reflective roofs have surfaces that reflect sunlight and emit heat more efficiently than hot or dark roofs, and therefore keeping them cooler in the Sun. That is, roofs with high solar reflectance and high infrared emittance can be called cool roofs. A cool roof is not a new concept; traveling pictures from the Mediterranean and the Middle East also show the scenery of homes with white roofs and walls. These are actually cool roofs, and have for thousands of years been a traditional architectural feature (Vickers, 2017). The solar reflectance (SR) (reflectivity or albedo) and infrared emittance (or emissivity) are two surface properties that affect the thermal efficiency of these roof surfaces (Sadineni et al., 2011).

Solar reflectance, also known as albedo, refers to the reflection of solar energy as it comes into contact with the surface material. Thermal emittance refers to the radiant emittance of the heat of a particular object in the form of infrared or thermal radiation, which relates to how easily the surface cools itself (Zingre et al., 2015a; Vickers, 2017).

A “cool roof” as a roofing system that refuses solar heat and holds surfaces cooler below the Sun is defined by The European Cool Roofs Council. A “cool roof” is ordinarily obtained by using cold materials on the external surface. So, these kinds of materials can decrease solar radiation absorption while releasing the heat received by the roof (Chang et al., 2008). The cool roof technology is more cost-effective and uncomplicated to perform in all domestic and commercial buildings (Rawat and Singh, 2021b). Cool roofs reflect a substantial fraction of incoming sunlight and retain the roof surface lower than conventional roofs, decreasing heat conduction into the building and its cooling load. This cool roof appearance performs it most beneficial when solar radiation’s intensity is tremendous, and the highest daily deviation happens (Razykov et al., 2011). There are somewhat differing descriptions for cold materials. Whereby, cold materials must have a solar reflectance originally equal to or greater than 0.65 for ES-ENERGY STAR (Yang et al., 2020). After 3 years, its requirement is higher than 0.50, while APEC Energy Working Group (De Masi et al., 2018) recognized having at least a reflectance of 0.70 and a thermal emissivity of 0.75.

Consequently, when the surface material has higher albedo and emissivity, the thermal fluctuations of the surface will be lower. Moreover, the thermal emittance, i.e. the capability of the roof surface for infrared radiations, is another significant factor in the thermal performance of roofs. That is, the higher their thermal emittance, the faster the roofs will lose heat and cool down (Suehrcke et al., 2008). Cool roof and green roof approach afforded and aided conceive thermal comfort for inhabitants and the energy saving of buildings (Lamnatou and Chemisana, 2015) (Shafique et al., 2018; Gilabert et al., 2021). A sustainable initiative and attracting energy scientists, architects, and urban planners to create better thermal comfort conditions and energy conservation and urban property growth are provided by Cool roofs and Green roofs (Saadatian et al., 2013). Beom-SoonHan examines the effects of cool roofs on turbulent coherent structures and ozone air quality, and analysis shows that cool roofs weaken the effects of turbulent coherent structures on O_3 concentration. (Han et al., 2020).

The effect of solar radiation on sunny days, the lack of infrared heat during the night, and the complications of heavy rainfall affect the roof more than any other building component (Al-Obaidi et al., 2014; Vellingiri et al., 2020). Moreover, as reported by Akbari and Matthews in their 2012 study (Akbari and Matthews, 2012), roof surfaces of buildings account for 20% in less urban areas, while this is up to 25% in cities with high density levels, and therefore the key effects of roofs on air and surface temperature in urban areas can be understood.

On this account, roofs can be used as specific enveloping elements for which revolutionary technology can offer considerable energy savings and lead to the enhancement of indoor thermal conditions. As a consequence, the implementation of efficient passive solar architecture measures into roofs would not only contribute significantly to the use of solar energy on a building scale, but would also help significantly to minimize the negative environmental impact on the city scale.

Cool roofs, i.e. roofs with a high level of solar reflectance and a high level of infrared emittance, are one of the most feasible and efficient passive techniques that can be applied to equip new buildings as well as to retrofit old ones. Additionally, green roofs reduced solar radiation receiving 60% radiation and diminished air conditioning energy among 25–80% (Besir and Cuce, 2018). Taizo Aoyama researches explain that a self-cleaning paint, based on an acrylic silicone polymer, efficiently keeps a high solar reflectance and limits dirt from adhering (Haberl et al., 2004). Some papers have focused on cool roof martials (Akbari and Levinson, 2008; Urban and Roth, 2010; Zinzi, 2010). Tim Sinsel studies the super cool materials. The results also revealed that super cool roofs could lower pedestrian-level air warmth in some areas by up to 2.4 K (Konopacki et al., 1998).

Among the limited studies on the form of a review article, reference may be made to the study conducted by Testa and Krarti (2017), in which the literature on cool roofs and switchable roofing materials are compiled and summarized as a tool for energy savings in buildings. While their study focused on energy savings and penalties for cool roofs, they nevertheless delivered a concise report on additional advantages and limitations of this technique. In the same direction, the 2014 Al-Obaidi et al. (Vickers, 2017). study provided a review of passive cooling strategies, including reflective and radiative roofs in tropical houses in Southeast Asia, and discussed the physical attributes of these approaches. However, as a more comprehensive study, the literature review by Haberl and Cho (Haberl et al., 2004) analyzed seventy-two articles from various sources, both quantitative and qualitative research on cool roofs, and provided a valuable summary of the potential energy performance of this passive technique based on different roof configurations.

While typical roofing materials have an SR of 0.05–0.25, applying reflective roof coating may raise the SR to more than 0.60. Many roofing materials have an infrared emittance of 0.85 or greater, apart from metals with a low infrared emittance of around 0.25. Hence, while metals are highly reflective, namely their SR is greater than 0.60, bare metal roofs and metallic roof coatings appear to get hot as they cannot efficiently emit the absorbed heat as radiation. However, adding special roof coatings may elevate the infrared emittance of bare metal roofs (Sadineni et al., 2011). Albeit, some studies have revealed that a roof with lower thermal emittance such as metal surfaces but extremely high solar reflectance can still remain cool in the sun (Akbari and Levinson, 2008). Lighter-colored surfaces have greater reflectance values than dark surfaces. In fact, the solar reflectance is close to 0 for black surfaces and close to 1 for white surfaces. Besides color, the roughness of the surface and the existence of contaminants can also influence the solar reflectance of the roof. Clean and polished materials have higher SR values (Testa and Krarti, 2017).

Hence, one of the easiest ways to apply cool roofing techniques is to shift from dark color finishes to light colors. (Zinzi, 2010). investigated the influence of color on the thermal profiles of the building material by monitoring the average daily surface temperature and temperature range of a number of mosaic and concrete samples. the color has a significant impact on the thermal performance of the material in such a way that

TABLE 1 | Correlation between roof temperature and two variables of Solar reflectance and Infrared emittance. (Adopted from (Konopacki et al., 1998)).

Roof surface	Solar reflectance	Infrared emittance	Temperature rise (°C)
Bitumen–smooth surface	0.06	0.86	46.1
Bitumen–white granules	0.26	0.92	35
Built-up roof—dark gravel	0.12	0.90	42.2
Built-up roof—light gravel	0.34	0.90	31.7
Asphalt shingles—black granules	0.05	0.91	45.6
Asphalt shingles—white granules	0.25	0.91	35.6
Shingles—white elastomeric coating	0.71	0.912	12.2
Shingles—aluminum coating	0.54	0.42	28.3
Galvanized Steel	0.61	0.04	30.6
Aluminum	0.61	0.25	26.7

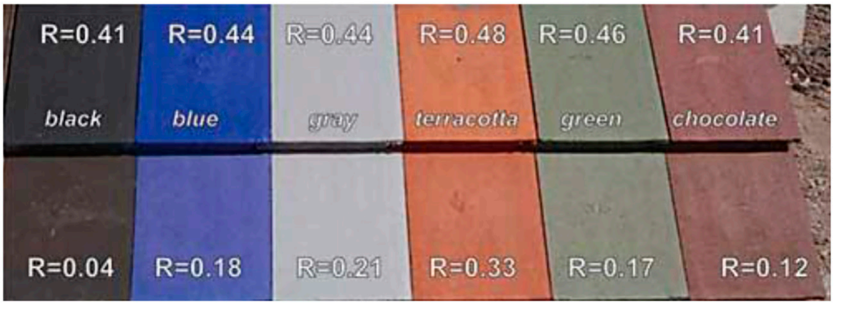

FIGURE 2 | Comparison between solar reflectance of Cool colored tiles **(top)** and ordinary colored tiles **(bottom)** (Source: American Roof tile Coatings and Lawrence Berkeley National Laboratory as cited in (Urban and Roth, 2010)).

there is a difference of about 10°C between the black and white color of the mosaic samples and about 12°C for the concrete samples. Moreover, the light color mitigates the range of thermal fluctuations, i.e. the difference between the maximum and minimum material temperature. (Zinzi, 2010).

3.2 Cool Martials

That is to say, higher solar reflectance and higher thermal emissions result in lower roof surface temperatures and prevent heat from flowing to the building compared to dark and hot roofs that absorb more than 90% of the incident solar radiation that induces temperatures above 66°C (Urban and Roth, 2010). **Table 1** shows the degree of these two factors in some common roof finishes. As can be observed, if the solar reflectance and infrared emission are higher, the temperature of the roof would be lower.

Solar energy intensity ranges from 250 to 2,500 nm in wavelengths. White or light-colored cool roof products reflect visible wavelengths, whereas colored cool roof products reflect in the infrared energy range. In view of the demand for colored roofing products for many buildings, manufacturers have tried to develop cool colored products that reflect near-infrared or infrared wavelengths ranging from about 700 to 2,500 nm. That is, as **Figure 2** shows, by employing cool coating material for each particular color, the solar reflectance of the roof tiles has significantly decreased.

Based on the widespread acceptance of cool roofs in recent years, various innovative cool coating materials and implementing technology have been developed and this procedure is also underway. **Table 2** illustrates the most common types of cool roofs that are already available on the market.

4 RESULT AND DISCUSSION

4.1 Elaboration of Benefits and Drawbacks

The subject of passive solar architecture covers a wide range of techniques, among which the application of solar reflective finishes for roofing systems has been of considerable interest over the last few decades. That is, there has been growing concern about the potential benefits of applying cool finishes to roof surfaces of buildings. The use of cool roofs to enhance comfort conditions and minimize energy consumption in dwellings and more commonly used buildings, such as educational, administrative, commercial, and cultural facilities, has therefore been examined in a large number of experimental and theoretical studies. As far as residential buildings are concerned, one may refer to the 1998 study by Parker et al. (1998), which carried out a series of experiments in Florida residences during the summer to measure the effect of increasing solar reflectance on space cooling loads. In the same direction, Synnefa et al. (Vickers, 2017) analyzed the effect of cool roof coatings on cooling and heating loads and the indoor thermal comfort conditions of residential buildings in 27 cities around the world, reflecting various climatic conditions.

TABLE 2 | A comparative report on the potential of cool roofs in terms of city scale as well as global scale, based on the main related publications (Developed by the author).

Scholar (year)	Outline of the study (method—Location—key Discussion)	Major findings on the potential of cool roofs
Rosenfeld et al. (1998)	**Method:** Software simulations **Location:** Los Angeles, United States **Key Discussion:** The potential of cool roofs and pavements for heat island mitigation and deceleration of smog formation	• It is possible to decrease the heat island of the studied area by as much as 3°C • In L.A., cooler roof and pavement surfaces and 11 million more shade trees are expected to reduce the ozone excess by 12% and marginally less in other smoggy cities
Taha et al. (1999)	**Method:** Software simulations three-dimensional, Eulerian, mesoscale meteorological model (CSUMM) **Location:** 10 different urban areas, United States **Key Discussion:** The potential impacts of large-scale increases in surface albedo and vegetative fraction on the meteorological conditions and energy usage	• Whereas in most of the analyzed areas heat islands of 1–2°C were measured, the application of cooling strategies can almost compensate that in most of these areas • The energy effect of a reduction of 1–2°C in space-average air temperatures, is a decrease of up to 10% in peak electricity demand and an annual cost savings of $10–35 per 100m2 of roof area, depending on the type of building and the region
Synnefa et al. (2007)	**Method:** Numerical simulations The meteorological model used with the modified Medium-Range Forecast (MRF) urban atmospheric boundary layer **Location:** Athens, Greece **Key Discussion:** The potential impact of cool roofs on city-scale ambient temperatures and UHI mitigation Two scenarios were compared, a moderate and an extreme increase in albedo	• The temperature depression at 2-m height was as high as 1.5°C for a moderate modified albedo (0.63) and the temperature depression was 2.2°C for an extreme modified albedo (0.85) • Implementing high albedo strategies reduces the heat island intensity by 1–2°C on average
Oleson et al. (2010)	**Method:** Urban canyon model coupled to a global climate model **Location:** All over the world **Key Discussion:** The effects of the global installation of white roofs on heat island mitigation	• The annual mean heat island decreased by 33% on average for all urban areas • The maximum urban daily temperature reduced by 0.6°C and the minimum daily temperature reduced by 0.3°C • At high latitudes in winter, the rise in roof albedo is less useful in alleviating the heat island due to low incoming solar radiation, the high albedo of snow being intercepted by roofs
Jo et al. (2010)	**Method:** On-site data collection (surface temperatures and reflectivity) was used in conjunction with the as-built drawings to create a building energy simulation model **Location:** Arizona, United States **Key Discussion:** The impact of applying cool roofs on resulting pollution emission mitigation	• As regards pollution emission mitigation, reductions of 90.33 and 173.88 tons of carbon dioxide (CO_2) emissions per year for the 50% cool roof and 100% cool roof can be achieved, respectively
Akbari and Matthews (2012)	**Method:** Software simulations **Location:** All over the world **Key Discussion:** Impact of cool urban surfaces (roofs and cool pavements) on urban heat islands mitigation and reduction of CO2 emission	• By applying cool roofs and cool pavements in urban areas, the average albedo of the urban area may increase by around 0.1 • It is predicted that increasing the albedo of urban roofs and paved surfaces worldwide would result in a negative radiative forcing equivalent to at least 40–160 Gt of CO_2 released
Xu et al. (2012)	**Method:** Field-based analytical method **Location:** – **Key Discussion:** The effect of cool roofs on energy savings in cooling, to moderate urban heat island, and to decrease greenhouse gas (GHG) emissions	• Measured annual energy savings from whitening of formerly black roofs varied from 20 to 22 kWh/m^2 of roof area, leading to a 14–26% reduction in cooling energy usage • The application of white coatings to uncoated concrete roofs has resulted in annual savings of 13–14 kWh/m^2 of roof area, corresponding to a 10–19% cooling energy saving • The annual direct CO_2 reduction related to the reduced cooling energy consumption was calculated to be 11–12 kg CO_2/m^2 of flat roof area
Santamouris (2014)	**Method:** A critical review Combining and reviewing current theoretical and experimental evidence in order to compare and homogenize findings **Location:** – **Key Discussion:** Effect of green and reflective roof mitigation techniques when applied on a city scale	• As for the global rise in albedo in the city, the predicted mean decrease in average ambient temperature is close to 0.3 K per 0.1 rises in albedo, whereas the related average decrease in peak ambient temperature is close to 0.9 K • When only cool roofs are regarded, the predicted rate of depression of average urban ambient temperature differs between 0.1 and 0.33 K per 0.1 increase in albedo roofs with a mean value of close to 0.2 K. As regards green roofs, while implemented on a city scale, the average air temperature may be lowered between 0.3 and 3 K • Cool roofs are more beneficial for UHI mitigation in sunny climates, whereas green roofs have a higher UHI mitigation capacity in cold climates

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TABLE 2 | (*Continued*) A comparative report on the potential of cool roofs in terms of city scale as well as global scale, based on the main related publications (Developed by the author).

Scholar (year)	Outline of the study (method—Location—key Discussion)	Major findings on the potential of cool roofs
Li et al. (2014)	**Method:** Weather Research and Forecasting (WRF) model in combination with the Princeton Urban Canopy Model (PUCM) **Location:** Baltimore-Washington metropolitan area, United States **Key Discussion:** Mitigation of the urban heat island (UHI) effect The cooling impacts of cool and green roof strategies, i.e. reductions in the surface and near-surface UHIs scale were compared during the heat wave period (June 2008)	• Decreases in surface and near-surface UHI scales almost linearly with green and cool roof fractions • The efficiency of cool roofs and green roofs are mainly influenced by albedo and soil moisture, respectively • In the case of cool roofs, the additional advantages or penalties from changing albedo values were significant. When the cool roof fraction is 50%, changing the albedo value from 0.7 to 0.9 (unusually high for current cool roof standard) will result in an additional 0.79°C reduction in UHI surface and an extra 0.14°C decrease in near-surface UHI (at peak temperatures)
Gagliano et al. (2015)	**Method:** A numerical comparative analysis **Location:** Catania, Italy coastal Mediterranean areas **Key Discussion:** Three types of roofs, i.e. a standard roof (SR), a cool roof (CR), and a green roof (GR) were compared in terms of the dynamic thermal activity of roofs and their effect on UHI mitigation	• For non-insulated roofs, the standard configuration achieved the maximum outer surface temperature, with a peak value of approximately 49.0°C, while the green roof had the lowest outer surface temperature, with a peak value of approximately 34.0°C. The temperature profile of the cool roof dropped between the above-mentioned profiles, with a peak value of approximately 43.0°C • Regarding inner surface temperatures, the traditional roof has reported the worst results, with a peak value of about 33.0°C, followed by the cool roof with a peak value of about 31.0°C. The green roof configuration has the lowest inner surface temperature, with a peak value of around 26.0°C
Costanzo et al. (2016)	**Method:** Software simulation Annual dynamic simulations for a sample office building were performed to measure energy efficiency (heat fluxes and primary energy needs) and external roof temperatures for five different scenarios: existing roof, green roof without irrigation (dry), green roof with an appropriate irrigation schedule, and cool roofs with two different values of solar reflectance (r = 0.65 and r = 0.80) **Location:** Three Italian cities with different climatic conditions **Key Discussion:** A comparison between cool roofs and green roofs for energy savings in buildings and the potential to mitigate the UHI effect	• Cool roofs are the most appropriate method for decreasing the temperature of the exterior roof surface in any climate: by using very efficient cool paint (r = 0.8), peak reductions of between 15 and 25°C are expected in the summer, although this effect is less pronounced in the afternoon • The sensible heat fluxes emitted from the roof to the outside atmosphere are reduced in each city by using both green roofs (from 42 to 75%, depending on the climate) and cool roofs (about 75% when r = 0.65, and even more when r = 0.80) • Cool roofs, if r > 0.65, are a more successful option than green roofs to overcome the UHI effect
Imran et al. (2018)	**Method:** Weather Research and Forecasting Model (WRF) coupled with the Single Layer Urban Canopy Model **Location:** Melbourne, southeast Australia **Key Discussion:** Efficacy of green roofs as a feasible urban heat island (UHI) mitigation strategy	• The maximum roof surface UHI is lowered by 1°C–3.8°C during the day by raising the green roof fractions from 30 to 90%, and by 2.2°C–5.2°C by raising the cool roof albedo from 0.50 to 0.85 • Cool roofs are more effective than green roofs to minimize UHI with potential variations of up to 1.4°C • The reduction in UHI varies linearly with the rising green roof fractions, but somewhat non-linearly with the rising albedo of cool roofs • Green roofs enhance human thermal comfort by reducing the Universal Thermal Comfort Index by up to 1.5°C and 5.7°C for pedestrian and roof surface levels, respectively, and by 2.4°C and 8°C for cool roofs at the same levels
Morini et al. (2018)	**Method:** Software simulations Weather Research and Forecasting (WRF) mesoscale model **Location:** Rome, Italy **Key Discussion:** Effect of albedo enhancement on mitigating urban heat island	• The simulation results reveal that the rise in albedo contributes to a drop in 2-m air temperature during the day and night • The rise in albedo provides very positive results in terms of UHI mitigation, lowering the temperature in the urban area by up to 4°C during the day and marginally rising (up to 1°C) at certain places during the night relative to the control cases
Yang et al. (2018)	**Method:** Software simulation (Numerical comparative analysis) A comparison between cool and green roof solutions was rendered in a tropical climate by means of dynamic simulations, taking into account climatological, thermal, optical, and hydrological variables **Location:** Singapore **Key Discussion:** The UHI reductions for the separate green/cool roof situations, the daily heat fluxes fluctuations, and the thermal energy reduction of buildings	• During peak hours (9 a.m.–5 p.m.) cool roofs reduce heat gain by about 0.14 KWh/m^2 (8%) and green roofs reduce considerably less to about 0.008 KWh/m^2 (0.4%). • For the entire summer design day, cool and green roofs reduce the heat gain by 15.53 (37%) and 13.14 (31%) KWh/m2 respectively • Cool roofs have a higher mitigation capacity compared to green roofs for tropical climate conditions, as vegetation will add covert heat flux owing to evapotranspiration and high maintenance requirements

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TABLE 2 | (*Continued*) A comparative report on the potential of cool roofs in terms of city scale as well as global scale, based on the main related publications (Developed by the author).

Scholar (year)	Outline of the study (method—Location—key Discussion)	Major findings on the potential of cool roofs
Macintyre and Heaviside (2019)	**Method:** Software simulations WRF mesoscale meteorological model **Location:** West Midlands, United Kingdom **Key Discussion:** Possible effects of cool roofs on population-weighted temperature reduction and urban heat island (UHI) mitigation	• City center summer UHI intensity was 2.0°C (2.6 C at night) reaching a maximum of 9°C • By applying cool roofs (albedo 0.7), the population-weighted temperature decreased by 0.3°C, corresponding to 23% of UHI intensity, which could potentially compensate for 18% of the seasonal heat-related mortality associated with UHI (corresponding to 7% of the overall heat-related mortality) • Cool roofs could minimize total heat-related mortality by 8% during heatwave periods, and compensate for 25% of that attributable to the UHI.
Lynn and Lynn (2020)	**Method:** Experimental study using Urban Canopy Model (UCM) in the Weather Research and Forecasting Model (WRF) **Location:** Jerusalem and Tel Aviv, Israel **Key Discussion:** The potential impact of green and/or cool roofs to reduce summertime temperatures and mitigate UHI	• The rise in albedo (cool roofs) had a greater effect on roof surface radiometric temperatures than on the roof with irrigated soil and vegetation • Cool roof surface temperature variations were about 20°C, compared to between 10 and 15°C for moist soils with vegetation • The effect of differing albedo levels on 2-m surface temperature was roughly 0.4°C and the effect of varying soil moisture was 0.1°C

However, for non-residential buildings, Akbari et al. (2005) monitored the impact of cool roofs on energy usage and environmental parameters in six California buildings at three separate locations. In the same direction, Romeo and Zinzi (2013) recorded the results of a large application in an office/laboratory building belonging to a school campus in Trapani, the location that enjoys Mediterranean climate on the west coast of Sicily in Italy.

Cool roofs have an outer surface covered with specific materials that are capable of minimizing solar absorption and maximizing thermal emittance. Therefore, they are able to sustain lower surface temperatures and minimize the heat transfer to the building. In particular, solar absorption is reduced by increasing the solar reflectance of the roof, defined as a fraction of the solar radiation that is diffusely reflected away from the surface (Testa and Krarti, 2017).

Principally, the benefits of adding cool materials to roofs derive from their ability to reduce the surface temperature. In general, the advantages of cool roofs can be regarded on a building, city, and global scale. At the building scale, the use of cooling materials decreases the usage of cooling energy and the peak energy demand for ventilation, since less heat is transmitted from the cooler roof to the building (Santamouris et al., 2011). The energy performance of cool roofs and their ability to provide thermal comfort in residential and non-residential buildings have been the subject of both experimental and numerical studies.

In addition, the heating penalty for this measure is also considered in a variety of papers. While a cool roof can reduce the cooling load of the building during warm months, it can unfortunately raise the heating load in cool months, thereby reducing its overall efficiency (Testa and Krarti, 2017). That is, though applying cool roofs can help decrease cooling loads in warm climates, the same cool roofs with high solar reflectance can also increase thermal heating loads and energy consumption in buildings during heating seasons, particularly in colder climates (Akbari and Levinson, 2008). In the same vein, based on EPA reports, this rise is much less significant than the concomitant decrease in cooling load, resulting in positive net savings in warm/moderate climate conditions. This is supported by the reason that, during the winter, the sun is far lower in the sky and the solar radiation on the horizontal surface is less severe. Hence, there is a greater risk of overcast clouds and less solar efficiency (fewer hours of sunshine) meaning that less overall energy falls on the earth to be stored or transmitted over the same amount of time as during the summer.

A thorough understanding of the energy performance of cool roofs requires a review of the related research, a summary of the findings, and an analogy between them. Haberl and Cho (Haberl et al., 2004) have arguably made one of the most noteworthy attempts in this respect, as they provide a relatively extensive review study on the energy efficiency of cool roofs based on seventy-two articles, although today it can somehow be regarded not to be state-of-the-art. Their findings, however exclusively for typical US buildings, revealed that cooling energy savings in residential and commercial buildings ranged from 2 to 44% and averaged around 20%; in addition, peak cooling energy savings from cooling roofs ranged from 3 to 35%, depending on the level of ceiling insulation, duct placement, and attic configuration. Although their approach could be insightful, their research is not only somehow outdated today, but also limited to a certain location and climatic condition. However, in order to provide a more inclusive and state-of-the-art analysis of the energy performance of cool roofs on a building scale, a review of the most relevant studies of different climatic conditions across the past 2 decades has been reported in **Table 3**, including their basic principles and major findings.

The application of cool coatings on the roof not only enhances their thermal efficiency but also decreases thermal stress, which helps to extend the life of the roof and minimize the cost of roof maintenance. As a matter of theory, material deterioration is consistent with chemical reactions that proceed quicker with higher temperatures, as cool materials lower the surface

TABLE 3 | A summarized review of the energy performance of cool roofs at the building scale on the basis of main related publications (Developed by the author).

Scholar (year)	Location climatic condition	Basic principles of the study	Remarks on the energy performance of cool roofs
Parker et al. (1998)	Florida, United States Humid subtropical climates	The peak power demand and cooling energy usage of residential buildings with an increased solar reflectance roof for 11 Florida homes during the summer months have been monitored	• While the solar reflectance before retrofitting ranged between 0.08 and 0.25, it improved dramatically after such a range of 0.59 and 0.73 • The savings in cooling energy usage were between 2 and 42%, and the decrease in Utility Coincident Peak Demand was between 11 and 30%. The overall use of cooling energy was decreased by 19%
Konopacki et al. (1998)	California, United States Mediterranean dry summer climate	Summer daily cooling energy savings from high reflective coatings, along with roof surface temperature, indoor and outdoor air temperatures, were assessed for three commercial buildings in California: two medical office buildings in Gilroy and Davis and a retail store in San Jose	• The average increase in roof solar reflectance for all three buildings was 0.40 • The cooling electricity use was decreased by 67 W h/m2 (18% savings) in the Davis medical office, 39 W h/m^2 (13% savings) in the Gilroy medical office, and 4 W h/m^2 (2%) in the San Jose retail store • The roof surface temperatures of all three buildings had reduced by an average of about 12°C
Akbari (2003)	Nevada, United States dry-summer subtropical	The cooling energy usage of two small (14.9 m^2) non-residential buildings in Nevada was measured during the summer of 2000. Buildings were first monitored for 1.5 months without any alterations in order to create basic conditions. Then, the roofs of the buildings were coated with reflective white coatings	• After application of the reflective coatings, the solar reflectance value of the roof was increased on average from 0.26 to 0.72 • The average daily electricity savings monitored is approximately 33 Wh/m^2 (1.5% savings) and the total annual savings was approximately 125 kWh per year (8.4 kWh/m^2)
Akbari et al. (2005)	California, United States Hot-summer Mediterranean climate & Desert climate	Six different types of commercial buildings were retrofitted with high reflectance white coatings or white PVC single-ply membrane at three different geographical sites in California to detect the impact of highly reflective roofs on cooling and peak load variability and evaluate the energy performance of the roofs	• Increasing the solar reflectance of roofs by 0.33–0.60 reduced the peak temperatures by 33–42 _C and the daily cooling energy consumption by 4, 18, and 52% in a cold storage facility, a school building, and a department store building, respectively • High reflective roofs are capable of achieving 5–40% cooling load savings and 5–10% peak demand savings
Synnefa et al. (2007)	Different climatic conditions	The effect of cool roof coatings on cooling and heating loads and the indoor thermal comfort conditions of residential buildings from 27 cities around the world, reflecting different climatic conditions, was investigated using software simulation	• Increasing the roof solar reflectance reduces cooling loads by 18–93% and peak cooling demand in air-conditioned buildings by 11–27% • The hours of relative discomfort decrease by anywhere from 9 to 100% • The heating penalty (0.2–17 kWh/m^2 year) was less consequential than the reduction of the cooling load (9–48 kWh/m^2 year)
Suehrcke et al. (2008)	Townsville, Australia Tropical savanna climate	The equation for the average daily downward heat flow of the sunlit roof is derived and the influence of the color on the roof heat gain has been quantified by building simulation	• Based on the derived equation, the light-colored roof has about 30% lower overall heat gain (air temperature difference and solar-driven) than the dark-colored one
Oliveira et al. (2009)	Brazil Humid tropical and subtropical climate	The numerical study conducted for the calculation of heat gains and losses for four envelope conditions—i.e., insulated, high-albedo, wet surface, and a combination of the previous two—and compared to a concrete roof assumed to be the standard condition and as such low and high solar reflectance conditions for 14 cities were evaluated	• High albedo surfaces in subtropical areas have been found to be significantly efficient; that is, the reflective roof has resulted in a 61% reduction in annual heat gain compared to the conventional roof
Han et al. (2009)	Hong Kong Humid subtropical climate	A dynamic simulation model for the analysis of the transient heat transfer through various roofing systems has been defined and resolved by the control volume finite-difference method using an explicit scheme	• The cooling load reduction ratio varies from 1.3% for black painted surfaces to 9.3% for light painted envelopes • The total daily heat gain was decreased up to 20% using a lightweight roof with polyurethane insulation and a white painted surface

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TABLE 3 | (*Continued*) A summarized review of the energy performance of cool roofs at the building scale on the basis of main related publications (Developed by the author).

Scholar (year)	Location climatic condition	Basic principles of the study	Remarks on the energy performance of cool roofs
Ahmad (2010)	Rawalpindi, Pakistan, Humid subtropical climate	Evaluation of the perforation of the anti-solar insulated roof system, i.e. a concrete roof with thermal insulation and a reflective coating, through an experimental study	• The contribution of the bare concrete roof to heat gain was 55% of the total gain in the building, but the contribution of the roof decreased significantly after the installation of insulation and coatings to only 6%
Jo et al. (2010)	Arizona, United States Tropical and Subtropical Desert Climate	The assessment of energy savings and the reduction of surface temperature achieved by replacing the current flat roof of the commercial building with a more reflective cool roof surface material was carried out using a building energy simulation model	• Simulation modeling has shown that reductions of 1.3–1.9% and 2.6–3.8% of the overall monthly energy usage can be achieved from a 50% cool roof replacement already implemented and a potential 100% roof replacement, respectively • If this roof was built on a building with a moderate amount of insulation (concrete thickness of 0.05 m (2 in)), the reduction in electricity will be increased by up to 8.7% relative to the overall energy consumption
Shen et al. (2011)	Shanghai, China Humid subtropical climate	An experimental study on the effect of solar reflective coatings on building surface temperatures, indoor environments, heat gain, and energy use under real weather conditions in summer and winter. Three types of coatings were applied to similar buildings and their efficiency was compared to a series of three independent experiments: a free-floating case, conditioned spaces, and various envelope materials	• The results showed that, based on location, season, and orientation, the temperature of the exterior and interior surfaces can be decreased by up to 20°C and 4.7°C, respectively, using different coatings • The overall decrease in global temperature and mean radiant temperature was 2.3°C and 3.7°C in that order • The penalty for increased demand for heating can have a negative all-year effect in Shanghai, which is characterized by hot summers and cold winters
Synnefa et al. (2012)	Athens, Greece Mediterranean dry summer climate	The effect of the application of a cool roof membrane on the energy performance and thermal behavior of a non-cooled school building has been assessed	• The validated simulation results revealed a decrease of 1.5–2°C in indoor air temperature in summer and a decrease of approximately 0.5°C in winter • In addition, a 40% reduction in cooling energy load was recorded compared to a 10% rise in heating demand
Kolokotroni et al. (2013)	London, England Marine West Coast Climate	The effect of the application of reflective paint on a flat roof in a naturally ventilated office building was measured by experiments as well as thermal modeling. The environmental conditions (internal/external air and surface temperature) of the building were monitored before and after the cool roof was added during the summer	• Thermal comfort can be enhanced by an average of 2.5°C (operative temperature difference for a change of 0.5 in albedo), but the heating requirement could be raised by 10% at a ventilation rate of 2 air changes per hour • Overall energy consumption is lowered by between 1 and 8.5% due to an albedo of 0.1. The reflectivity of 0.6–0.7 is ideal for the London climate
Romeo and Zinzi (2013)	Sicily, Italy Humid subtropical climate	The monitoring was performed before and after the application of cool, eco-friendly white paint in an office/laboratory building belonging to a school campus. Monitoring data was used to calibrate the building model input into a dynamic simulation tool used to test building performance with a series of variants	• For a roof with an area of 700 m^2, the application of cool paint decreased the cooling load by 54% • The roof surface temperature decreases by up to 20°C while the average reduction of 2.3°C during the cooling season is achieved with respect to indoor thermal conditions
Pisello and Cotana (2014)	Perugia, Italy Temperate Humid subtropical climate	An innovative cool clay tile was developed for testing in a traditional residential building, and the thermal impact of a cool roof is measured through 2 years of continuous monitoring; the first year in its original configuration and the second year in its optimized configuration, with the final objective of quantifying both the summer benefits and the winter penalties of such a solution	• The year-round evaluation shows that the proposed cool roof solution has the maximum benefit of minimizing the summer peak indoor overheating by up to 4.7°C • The resulting winter maximum overcooling reduction would be 1.2°C

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TABLE 3 | (*Continued*) A summarized review of the energy performance of cool roofs at the building scale on the basis of main related publications (Developed by the author).

Scholar (year)	Location climatic condition	Basic principles of the study	Remarks on the energy performance of cool roofs
Hosseini and Akbari (2016)	North America cold-climate	Entire-building simulation analyses were conducted to measure the effect of snow accumulation on cool roofs during the winter months on energy usage in an office building in four cold climate cities in North America: Anchorage (AK), Milwaukee (WI), Montreal (QC), and Toronto (ON)	• Heating penalties for cool roofs are considerably smaller than is generally assumed in the case of snow on the roof • The yearly heating energy consumption of the building for a dark and cool roof without any consideration of snow is 85 and 88 GJ/100 m^2, respectively (3 GJ/100 m^2 penalty for a cool roof) in Anchorage • The annual heating energy for a dark and cool roof considering the impact of late-winter packed snow is 83 and 84 GJ/100 m2, respectively (1 GJ/100 m2 penalty for the cool roof) in Anchorage
Baniassadi et al.(2018)	Los Angeles, United States Mediterranean dry subtropical climate	Whole-building energy simulations were employed to measure the direct and indirect advantages of high-albedo roofs on single-family detached residential buildings in three locations (one coastal and two inland)	• The Large-scale installation of cool roofs over the region could result in savings of 24–41% in cooling energy bills for low-performance buildings • In unconditioned buildings, the increase in albedo can decrease the number of uncomfortable hours during the summer by up to 20%
Seifhashemi et al. (2018)	Queensland, AustraliaHumid subtropical climate	An experimental and computational study was conducted to quantify the benefits of retrofitting cool roof technology for the typical commercial building typology in Australia, i.e. single-story warehouse-style buildings	• By implementing cool roof technology, energy efficiency improved by shifting the space temperature towards the design set point (21–23°C) and thereby reducing the cooling energy demand • Energy savings can be achieved every month, with the greatest savings in the hottest months and no heating penalty in the cooler months • Adjusted for the Australian state and territory on the basis of computational models, annual CO2 emissions savings of between 1,530 and 2,680 kg of CO2 per warehouse-style building can be expected

temperature, they retard destructive reactions within the roofing materials. Besides, extreme thermal variations have significant damaging effects on roofing materials, and thus, as cool coatings mitigate these changes, the service life of roofs is extended. In a study conducted by Gagliano et al. (2015), a comparison was made between three different roofs, i.e. standard, cool and green roofs, in two scenarios as insulated and without insulation in terms of their dynamic thermal behavior. As their findings revealed (Gagliano et al., 2015), although the cool roof has not shown the capability of the green roof to mitigate thermal variations between the outer and inner surfaces of the roofs, this technology can reduce the outer surface temperature by up to 7°C compared to the standard case.

However, as has been pointed out, the benefits of cool roofs are not limited to building scale, as they have a considerable impact on the neighborhood and city scale and as a consequence on the global environment. Materials utilized in building envelopes and urban structures play an essential role in the urban thermal balance. They absorb solar and infrared radiation and dissipate part of the stored heat into the environment by convective and radiative processes that raise the atmospheric temperature. On a city scale, this effect leads to a rise in urban air temperature, namely the well-known phenomenon regarded as the Urban Heat Island (UHI) effect. This is characterized as the increase in air temperature in densely developed areas with respect to the surrounding countryside, and its major driver is the alteration of the land surface in the urban area, where the vegetation is substituted by paved roads and building surfaces (Costanzo et al., 2016).

As discussed in a variety of studies (**Table 4**), the application of cool materials on urban surfaces avoids the urban heat island effect (UHI) and slows down the smog formation by minimizing local air temperature. The advantages of cool pavements are due to the fact that raising the solar reflectance of the ground surface makes it cooler under the sun, decreases the convection of heat from the pavement to the air, and thus reduces the temperature of the surrounding atmosphere. In effect, City-scale use of cooling materials will theoretically minimize air pollution, both directly and indirectly. As (Rosenfeld et al., 1998) have clarified, the direct reduction in air pollution is due to the fact that less cooling energy is used; thus, fewer pollutants from power plants, i.e. harmful gases, such as CO2 or NOx, are generated, whereas indirect

TABLE 4 | Different methods of cool roof.

Method	Location	Function	Advantages	Disadvantage	Saving energy in year	References
a combination of efficient roof techniques (skylights and cool roof) along with high thermal inertia of the building	La Rochelle, France, Warm and Temperate	*commercial low-rise buildings*	an adequate passive cooling solution in summer	these answers could be not sufficient without the addition of the ground thermal inertia	33.8%	Lapisa et al. (2013)
cool roof solution consisting of prototype cool clay tile applied on a traditional residential building	Perugia, Italy, Warm and Temperate	traditional residential building	improve the thermal condition of the indoor environment	The offered cool roof provides penalties in winter	_	Pisello and Cotana, (2014)
Cool roof heat transfer (CRHT) model using the spectral approximation method	Singapore, Tropical	_	developed and verified against experimental performed in apartments with concrete roofs	Daily heat gain reduction was also achieved when the cool coating was applied on galvanized steel (metal) roofs, and this model even to ceilings and walls	54%	Zingre et al. (2015b)
Cool paint applied on the roof	Sicily and Jamaica	Houses	reducing cooling loads easiness of installation and capital cost	it is a worth- while retrofit options in locations with high solar radiation but also some heating demand	188 kWh/m^2/year for Jamaica	Shittu et al. (2020)
Thermochromic materials	Seven U.S. geographic locations		limiting undesired solar heat gain during the hot seasons and increasing solar heat gain during the cold seasons	The negative values indicate the penalties of energy consumption, cost, and equivalent carbon emission, which are especially found for static cool roofs in cold climates	7.7% of total energy consumption 21.7 kWh/m^2/year for the house in Silicy	Hu and Yu, (2019)
super-cool materials	the Los Angeles area (one coastal, and two inland)	residential buildings	the super-cool rooftop remains below the ambient air temperature throughout the year	suitable for environments with warm summers, moderate winters and it is not practical in cold climate	41%	Baniassadi et al. (2018)
switching cool roofs	in four US climate	_	that switchable roof insulations can substantially reduce both heating and cooling energy end-uses	building roofs is identifying the best control strategies to optimize the cool roof reflectance settings it is difficult to draw a direct relationship between roof reflectance and a control setting	19%	Zinzi et al. (2021)
metamaterial film-based radiative cooling	five cities in China, each in a different climate zone	The prefabricated buildings	The most useful method to use this metamaterial film-based radiative cooling is to combine it with buildings as cool roofs	is more suitable for buildings with higher roof area to floor area ratios, as this accounts for its relative lower cooling power of 110 W/m^2 on a daily average	28.9–43.0%	Ma et al. (2021)
calibrated model	five cities in India	_	The highest energy saving gained in the warm-humid climatic zone, and energy saving in hot-dry, composite, and temperate are also meaningful	cool roof use was seen not viable in the cold climatic zone due to the payback period of more than 5 years	Around 4%	Bhatia et al. (2011)
the application of a cool roof coating over a traditional roof rooms coated with high albedo paint	India	school buildings	Results indicate reduction in the roof surface temperatures and indoor air temperatures. Results prove that cool roofs are effective in improving comfort in rural buildings	the slope of the roof will have an impact on its effectiveness	14–26%	Garg et al. (2016)

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TABLE 4 | (*Continued*) Different methods of cool roof.

Method	Location	Function	Advantages	Disadvantage	Saving energy in year	References
double roof prototypes incorporating RBS (radiant barrier system)	Texas, United States Tropical	_	Decrease both the conduction and convection heat transfers from the roof to the ceiling of the building. They are blocking the radiation heat transfer between the roof and ceiling	The flow boundary layers of the two surfaces interfere with each other, and the disturbance in the channel occurs earlier, increasing heat transfer benefits and bringing more heat flow into the interior	70.0%	Chang et al. (2008)
Solar-reflective roofs	California	a retail store in Sacramento; an elementary school in San Marcos cold storage facility in Reedley	reduced the daily peak roof surface temperature of each building	cool, reflective roofs may cause an unwanted glare	52%	Akbari et al. (2005)

reductions in air pollution indicate the fact that the ozone-forming reaction that creates smog accelerates at higher temperatures, so the possibility of smog formation is diminished at lower urban air temperatures. Moreover, as Yang et al. (2018) argued, structures, pavements, and car parks keep the heat coming from the earth from dissipating into the cool night sky. As a result, the air temperatures in UHI maintain high even throughout the night, raising the need for air conditioning and the emission of air pollution and greenhouse gasses from fossil fuel plants.

For the sake of brevity and clarity, a concise report on the potential of cool roofs in relation to the city scale as well as the global scale was compiled in **Table 2**, including the main addressed subject concerning the effect of cool roofs as well as the major results of the studies.

Apart from the benefits of cool roofs on different scales, which have been mentioned in a number of studies, there are, however, some drawbacks that have been attributed to this technology in some texts. The most important issue in this regard is the fact that, since the use of cooling materials on roofs decreases the heat gain throughout the year, they not only minimize the cooling demand but also increase the demand for heating during the cold periods. However, as is typically documented in studies on locations with relatively long hot periods, such as studies by Synnefa et al. (2012)and Pisello and Cotana (2014), the increase in heating load during cold months is not that significant compared to the decrease in cooling load. But, when it comes to areas with longer and severe cold periods, as in the study conducted by Shen et al. (2011), increased demand for heating can have a substantial negative annual impact on total energy use. Another possible adverse consequence of lower surface temperatures from inactive cool roofs is the sensitivity to condensation within the roof assembly. In cold climates with short-tempered summers, lower surface temperatures of inactive cool roofs may increase moisture in the roofing construction by reducing the drying potential and enhancing the uncertainty of interstitial concentration (MoghaddaszadehAhrab and Akbari, 2013). The cool roof payback period is short compared to other methods, which can be 2 months (Zhang et al., 2016). Cool roofs, compared with photovoltaic panel roofs and roof gardens, maintain a lower surface temperature, improving passive cooling during nighttime (Abuseif and Gou, 2018). Accurate choice of this approach is required when heating is highly needed for a building to assess its performance before implementing it on the roofs of a building and avoiding its adverse consequence on heating loads.

Furthermore, as the efficiency of cool roofs is strongly linked to their solar reflectance, the accumulation of dirt and dust might reduce their effect (Urban and Roth, 2010). Thus, in areas where there is a high potential for dust to settle on the surface, the application of cool roofs could lead to some problems over time. Moreover, considering the nature of cool surfaces with high solar reflectance, they provide intense radiation in their surroundings, which may cause visual annoyance and undesired glare, particularly during clear sunny days (Al-Obaidi et al., 2014). Consequently, their use in the vicinity of critical areas that require a clear aerial view, such as airports, is not suggested.

In order to provide an informative detailed summary of the elaborated pros and cons of the cool roofs, one of the best approaches is to provide itemized factors that correspond to the relevant codified references. It should be remembered, of course, that some of these components are not essentially independent of each other and are in a causal relationship. For instance, as cool roofs reduce heat gain, they enhance the thermal comfort of indoor spaces and thus decrease energy demand for air conditioning, which in turn helps to reduce the peak demand for electricity and has a positive effect on lower electricity bills. However, though these components are in close, casual relationships with each other, each study approached the subject from a certain viewpoint and presented its report with a focus on specific components. Ergo, for the purpose of offering a clearer and more instructive summary, they are presented as separate components in **Table 5**. In addition, while the majority of codified sources pertaining to each item are in the form of research articles, in a few instances, certain review studies which

TABLE 5 | Summary of the advantages and drawbacks of cool roofs through the itemization and codification of the relevant sources (Developed by Authors).

Cool roofs			
Advantages	• reduce heat gain through the roof and enhance thermal comfort for indoor spaces. (Rabah, 2005; Chang et al., 2008; Razykov et al., 2011; Sadineni et al., 2011; Kamal, 2012; Al-Obaidi et al., 2014; Azari, 2014; Lotfabadi, 2015; Zingre et al., 2015a; Abdul Mujeebu and Alshamrani, 2016; Kannan and Vakeesan, 2016; Marrana et al., 2017; Pisello, 2017; Vickers, 2017; Shafique and Kim, 2017; Testa and Krarti, 2017; Ashraf et al., 2018; De Masi et al., 2018; Hu and Yu, 2019; Yang et al., 2020; Rawat and Singh, 2021a; Rawat and Singh, 2021b) • reducing cooling loads, minimizing demand for air conditioning and thus reducing energy bills. (Rosenfeld et al., 1998; Bilgiç, 2003; Cheikh and Bouchair, 2008; Suehrcke et al., 2008; Razykov et al., 2011; Singh et al., 2011; Akbari and Matthews, 2012; Kamal, 2012; Azari, 2014; Al-Obaidi et al., 2014; Lotfabadi, 2015; Zingre et al., 2015a; Abdul Mujeebu and Alshamrani, 2016; Akbari and Kolokotsa, 2016; Kannan and Vakeesan, 2016; Marrana et al., 2017; Shafique and Kim, 2017; Pisello, 2017; Testa and Krarti, 2017; Vickers, 2017; De Masi et al., 2018; Imran et al., 2018; Ashraf et al., 2018; Pradhan et al., 2019; Yang et al., 2020; Macintyre et al., 2021; Rawat and Singh, 2021a; Rawat and Singh, 2021b) • reduce thermal tension, which helps to prolong the lifespan of the roof and lessen the cost of roof maintenance. (Rosenfeld et al., 1998; Al-Obaidi et al., 2014; Lotfabadi, 2015; Abdul Mujeebu and Alshamrani, 2016; Shafique and Kim, 2017; Ashraf et al., 2018; Hu and Yu, 2019) • decrease the peak electricity demand. (Bilgiç, 2003; Rabah, 2005; Cheikh and Bouchair, 2008; Suehrcke et al., 2008; Sadineni et al., 2011; Singh et al., 2011; Kamal, 2012; Azari, 2014; Lotfabadi, 2015; Zingre et al., 2015a; Abdul Mujeebu and Alshamrani, 2016; Kannan and Vakeesan, 2016; Marrana et al., 2017; Testa and Krarti, 2017; Vickers, 2017; Ashraf et al., 2018; Imran et al., 2018; Pradhan et al., 2019; Yang et al., 2020) • prevent urban heat island effect (UHI) and decelerate smog formation by reducing local air temperature. (Rosenfeld et al., 1998; Bilgiç, 2003; Haberl et al., 2004; Cheikh and Bouchair, 2008; Suehrcke et al., 2008; Singh et al., 2011; Saadatian et al., 2013; Al-Obaidi et al., 2014; Azari, 2014; Abdul Mujeebu and Alshamrani, 2016; Akbari and Kolokotsa, 2016; Pisello, 2017; Testa and Krarti, 2017; Ashraf et al., 2018; Besir and Cuce, 2018; Shafique et al., 2018; Jeong et al., 2021; Rawat and Singh, 2021a; Hu and Yu, 2019; Lamnatou and Chemisana, 2015; Gilabert et al., 2021; Han et al., 2020; Vellingiri et al., 2020; Akbari and Matthews, 2012) • reduce air pollution, i.e. hazardous emissions from power plants such as carbon dioxide, sulfur dioxide and nitrous oxides. (Rabah, 2005; Santamouris et al., 2011; Singh et al., 2011; Kamal, 2012; Testa and Krarti, 2017; Macintyre et al., 2021; Rawat and Singh, 2021a; Rawat and Singh, 2021b) • slow down climate change by reducing the amount of heat trapped in the atmosphere. (Rosenfeld et al., 1998; Haberl et al., 2004; Chang et al., 2008; Akbari and Matthews, 2012; Saadatian et al., 2013; Azari, 2014; Lamnatou and Chemisana, 2015; Abdul Mujeebu and Alshamrani, 2016; Akbari and Kolokotsa, 2016; Ashraf et al., 2018; Besir and Cuce, 2018; Shafique et al., 2018; Hu and Yu, 2019; Han et al., 2020; Gilabert et al., 2021; Rawat and Singh, 2021a) • retard ozone concentration (particularly in dense urban area). (Cheikh and Bouchair, 2008; Santamouris et al., 2011; Testa and Krarti, 2017; Besir and Cuce, 2018; Hu and Yu, 2019)		
Flaws	• cool roofs attenuate heat gain throughout the year and therefore not only reduce cooling demand, but also increase energy consumption for heating. (Chang et al., 2008; Razykov et al., 2011; Akbari and Kolokotsa, 2016; Testa and Krarti, 2017; Ashraf et al., 2018; De Masi et al., 2018) • since the efficiency of cool roofs is connected with their solar reflectance, the accumulation of dirt and dust could diminish their impact. (Shafique and Kim, 2017; Ashraf et al., 2018) • reflective roofs may cause visual discomfort and an unwanted glare, and thus their implementation near sensitive areas such as airports is not recommended. (Rosenfeld et al., 1998; Lotfabadi, 2015; Akbari and Kolokotsa, 2016; Ashraf et al., 2018) • cool roofs are useful in low-rise buildings where the ratio of roof area to the surface area of the building is high, but it is not helpful for high-rise buildings. (Shittu et al., 2020) • general cool roof is effective for reduction of cooling load, but it has a problem of increasing heating load. (Yoon et al., 2018) • nocturnal natural ventilation is efficient to moderate indoor overheating compared to the cool roof (Kaboré et al., 2018) • static cool roofs can lead to significant heating thermal penalties in colder environments. Compared to the estimates from reported studies, one agent that may decrease the disadvantages of cool roofs is the buildup of snow on roofs during winter seasons. (Hosseini et al., 2018)		
Sources	(Urban and Roth, 2010; Shafique and Kim, 2017)	(Santamouris et al., 2011; Testa and Krarti, 2017)	(Chang et al., 2008; Synnefa et al., 2012)
	(Akbari and Levinson, 2008; Abdul Mujeebu and Alshamrani, 2016)	(Pisello and Cotana, 2014; Hu and Yu, 2019)	(Razykov et al., 2011; Kolokotroni et al., 2013)
	(Rosenfeld et al., 1998; Akbari et al., 2001)	(Lotfabadi, 2015; Xamán et al., 2017)	(Pisello and Cotana, 2014; Yang et al., 2020)
	(Konopacki et al., 1998; Kannan and Vakeesan, 2016)	(Rosenfeld et al., 1998; Frontini et al., 2012)	(Taha et al., 1999; De Masi et al., 2018)
	(Parker et al., 1998; Imran et al., 2018)	(Cheikh and Bouchair, 2008; Jo et al., 2010)	(Synnefa et al., 2007; Suehrcke et al., 2008)
	(Synnefa et al., 2007; Marrana et al., 2017)	(Xu et al., 2012; Rawat and Singh, 2021b)	(Oleson et al., 2010; Lamnatou and Chemisana, 2015)
	(Sadineni et al., 2011; Pradhan et al., 2019)	(Taha et al., 1999; Singh et al., 2011)	(Santamouris, 2014; Shafique et al., 2018)
	(Al-Obaidi et al., 2014; Ashraf et al., 2018)	(Rabah, 2005; Costanzo et al., 2016)	(Li et al., 2014; Gilabert et al., 2021)
	(Zinzi, 2010; Pisello, 2017)	(Bilgiç, 2003; Gagliano et al., 2015)	(Saadatian et al., 2013; Imran et al., 2018)
	(Akbari and Kolokotsa, 2016; Testa and Krarti, 2017)	(Al-Obaidi et al., 2014; Seifhashemi et al., 2018)	(Morini et al., 2018; Han et al., 2020)
	(Santamouris et al., 2011; Gilbert et al., 2017)	(Kamal, 2012; Baniassadi et al., 2018)	(Yang et al., 2018; Vellingiri et al., 2020)
	(Xu et al., 2012; Macintyre et al., 2021)	(Akbari et al., 2005; Azari, 2014)	(Akbari and Matthews, 2012; Macintyre and Heaviside, 2019)
	(Li et al., 2014; Jeong et al., 2021)	(Oliveira et al., 2009; Vickers, 2017)	(Besir and Cuce, 2018; Lynn and Lynn, 2020)
	(Akbari and Matthews, 2012; Rawat and Singh, 2021a)	(Han et al., 2009; Sadineni et al., 2011)	
		(Shen et al., 2011; Zingre et al., 2015a)	

provide insightful information on a particular item are also included in this summary.

Table 4 discusses more deeply the drawbacks and limitations, and advantages of the different methods on various climate conditions.

5 CONCLUSION

This review paper addressed the general features and operating mechanism of cool roofs and provided a comparative report on their energy efficiency and thermal performance through an extensive review of the most relevant studies, including a wide range of experimental analyzes and computational approaches based on software simulations conducted in different types of buildings under different climatic conditions. In addition, the pros and cons of this passive technique have been explained and a detailed summary has been drawn up as the itemized factors corresponded to the codified references. The concluding remarks may be noted as follows:

- Cool roofs can be considered an efficient passive solar technique that can be implemented fairly easily for new buildings as well as for the retrofitting of existing structures.
- Their operating mechanism is based on the application of materials as a surface coating with high reflectivity as well as high emissivity, and therefore both reflective and radiative approaches that boost heat dissipation can be developed in this regard.
- The benefits of this technique can be regarded on various scales: building-scale pros, such as providing thermal comfort, increasing energy efficiency, and helping to improve roof life-span; pros at the city and global scale, such as attenuating local air temperatures and thus preventing urban heat island effects and smog formation, reducing air pollution and slowing down climate change.
- As the analyzed studies have indicated the efficiency of cool roofs depends on certain criteria, including the climatic conditions, i.e. air temperature, relevant humidity and wind direction, general layout of the building, and building envelope properties, i.e. constituent layers profile, specifically the level of insulation.
- They minimize the heat gain throughout the year, thereby helping to reduce the cooling load while at the same time increasing the heating load.
- In the case of warm and temperate climate conditions, with a considerable cooling period, positive net energy savings have often been reported, with very low penalties for winter heating.
- Cool roofs can cause considerable heat penalties during cold seasons for locations with a severe heating season and therefore have a negative impact on the overall annual energy demand.
- Although cool roofs have significant advantages for their surrounding environment, especially in the case of large applications, they are however noticeably susceptible to the accumulation of dirt and dust and may also provide undesired glare, particularly during sunny days.
- As a guideline for future studies, it can be argued that while the energy efficiency of cool roofs has been widely examined in the hot or temperate climate zone, more detailed experimental and simulation analyses need to be performed when it comes to cold and continental climatic conditions in order to investigate their thermal output i.e. the resulting heating penalty, and also the relevant compensation strategies to outperform this negative output should be developed.

AUTHOR CONTRIBUTIONS

BA: paper draft version, data collection, paper formatting, and primary data analysis. MY: conceptualization, final editing, validating, data analysis. MB: general supervision. BV: paper revisions-supplementary data analysis-data analysis.

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