Journal of Engineering Science and Technology
Vol. 12, No. 8 (2017) 2120 - 2140

A REVIEW ON HEAT DISSIPATING PASSIVE COOLING TECHNIQUES FOR RESIDENTIAL BUILDINGS AT TROPICAL REGION

D. PRAKASH*

School of Mechanical Engineering, SASTRA University,
Thanjavur, Tamil Nadu, India- 613401
*Corresponding Author: prakash@mech.sastra.edu

Abstract

Thermal comfort is very essential for the occupants in a residential building without air-conditioning system especially in tropical region. Passive cooling is the only solution to achieve the required thermal comfort without sacrificing occupant's health with zero energy consumption. All passive cooling techniques are broadly categorized under (i) solar and heat protection, (ii) heat modulation and (iii) heat dissipation techniques. This paper reviews various techniques and advancements in passive cooling of buildings through heat dissipation approach. In the heat dissipation approach, the heat generated from various sources are reduced by natural ventilation and natural cooling.

Keywords: Thermal comfort, Natural ventilation, Natural cooling, Roof insulation, Residential building

1. Introduction

Energy consumption in the residential buildings has become a major fear in tropical regions where high temperature and humidity compels the occupants to use electro mechanical ventilation systems for making the indoor as thermally comfortable. Globally, buildings are responsible for approximately 40% of entire world's annual energy consumption and most of this energy was consumed for the provision of lighting, heating, cooling and air- conditioning [1]. The building sector represents about 33% of electricity consumption in India, with the commercial sector and residential sector accounting for 8%and 25% respectively [2]. Another serious issue

Nomenclatures

H	Height of building
L	Length of building
k	Thermal conductivity

Abbreviations

ASHP	Air source heat pump
BCSF	Binderless cotton stalk fiber board
COP	coefficient of performance
DPF	Date Palm fiber
EAHE	Earth to air heat exchanger
GSHP	Ground source heat pump
MC	Moisture content
NV	Natural ventilation
PCM	Phase change material
PU	Polyurethane
RPET	recycled polyester fibres
RSTIB	Rice straw
VBTW	Venetian blind trombe wall
WFW	woven fabric waste

identified in the mechanically cooled buildings is the cause of many health related problems. Some of the health problems are headache, heat strokes, dehydration, frostbite, lung diseases and etc. These health symptoms ultimately reduce the productivity level of the occupants. Hummelegaard et al. (2007) identified that naturally ventilated buildings provide a higher degree of satisfaction with the thermal environment and lower symptom among the occupants [3]. Hence the increase in the demand of electrical energy and many health-related symptoms associated with mechanically ventilated buildings forces the occupants to adhere towards passive cooling techniques. Passive cooling or natural cooling refers to the cooling of indoor without any form of energy input other than renewable energy sources. Passive cooling technique works on the principle of preventing heat from entering the interior or by removing heat from the building. The Passive cooling techniques is broadly classified under (i) Solar and heat protection techniques (ii) Amortization technique and (iii) Heat dissipation technique. Among the three categories, present work reviews the passive cooling strategies under heat dissipation category. The various strategies of heat dissipation from the building are shown in Fig. 1.

2. Natural ventilation

Natural ventilation is an effective sustainable strategy for occupant’s comfort in residential building. ASHRAE (1997) defines natural ventilation as an internal flow of air thorough open windows, doors, grilles and another planned building envelope penetrations from outside into a building. Natural ventilation system relies on natural driving forces, such as wind pressure and the thermal buoyancy effect between the building and its environment. The NV requires an appropriate understanding on principles of local wind patterns, climate conditions, airflow around the building, building orientation, pressurization and façade design [4]. Thus, engineer's consciousness and understanding on the above factors is required compulsorily for the suitable design of a naturally ventilated building with maximum energy advantages.

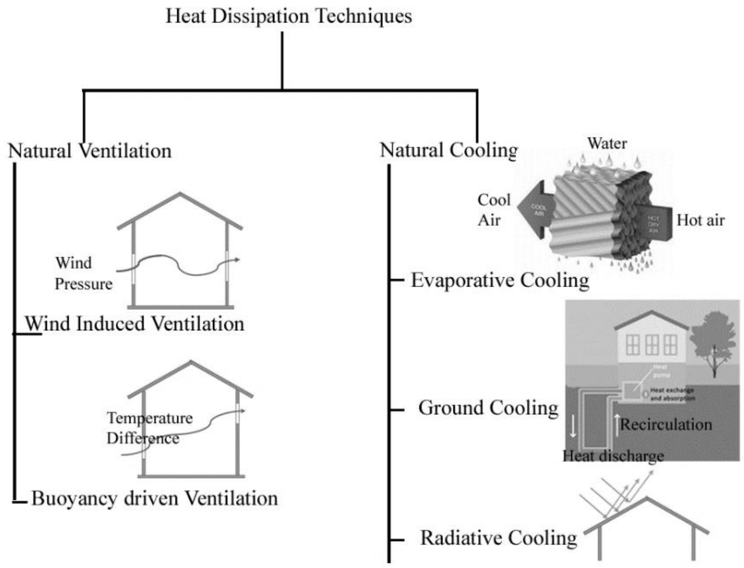


Fig. 1. Heat dissipation technique for passive cooling of buildings.

2.1. Wind driven ventilation

Wind driven ventilation occurs due to various pressures created on the building envelope by wind. The pressure differences drive the air into the building through the windward side opening, and drive air out of the building through leeward side opening. It depends on the external wind speed, direction, openings and building configurations. For proper wind-driven cross ventilation, the building length, L should be less than five times the ceiling height H [5, 6]. For long buildings with length $L/H > 5$, the wind-driven ventilation will not be effective. Figure 2 shows some the techniques to enhance wind driven ventilation.

Chu and Chiang [7] studied the effect of aspect ratio of the building and identified that the building length should be five times the ceiling height. Also, the ventilation rate of a short building is higher due to the larger pressure difference between the windward and leeward side. Chu and Chiang [8] studied the cross-ventilation performance of the building with some obstacles like large furniture, short partition walls. This study identifies that the external pressure remains the same, in spite of obstacle sizes and the resistance factor is a function of the internal blockage ratio and location.

Peren et al. [9] studied the impact of roof geometry of an isolated leeward saw tooth roof building on cross ventilation. The roof geometry includes straight, concave, hybrid (concave – convex) and convex shapes. It shows that a straight or convex roof geometry can maximize the under pressure in the wake of the building, where the outlet opening is located, which results in enhanced wind-driven cross-ventilation flow.

Lo and Novoselac [10] developed a correlation between the cross-ventilation rate to the velocity component of the approaching wind that is normal to the inlet opening. Peren et al. [11] studied the impact of eaves on cross-ventilation of a generic isolated leeward saw tooth roof building. Implementation of both windward and leeward eaves results in an increase of the volume flow rate of 24%, which is 3% more than the sum of the increases by the two eaves separately.

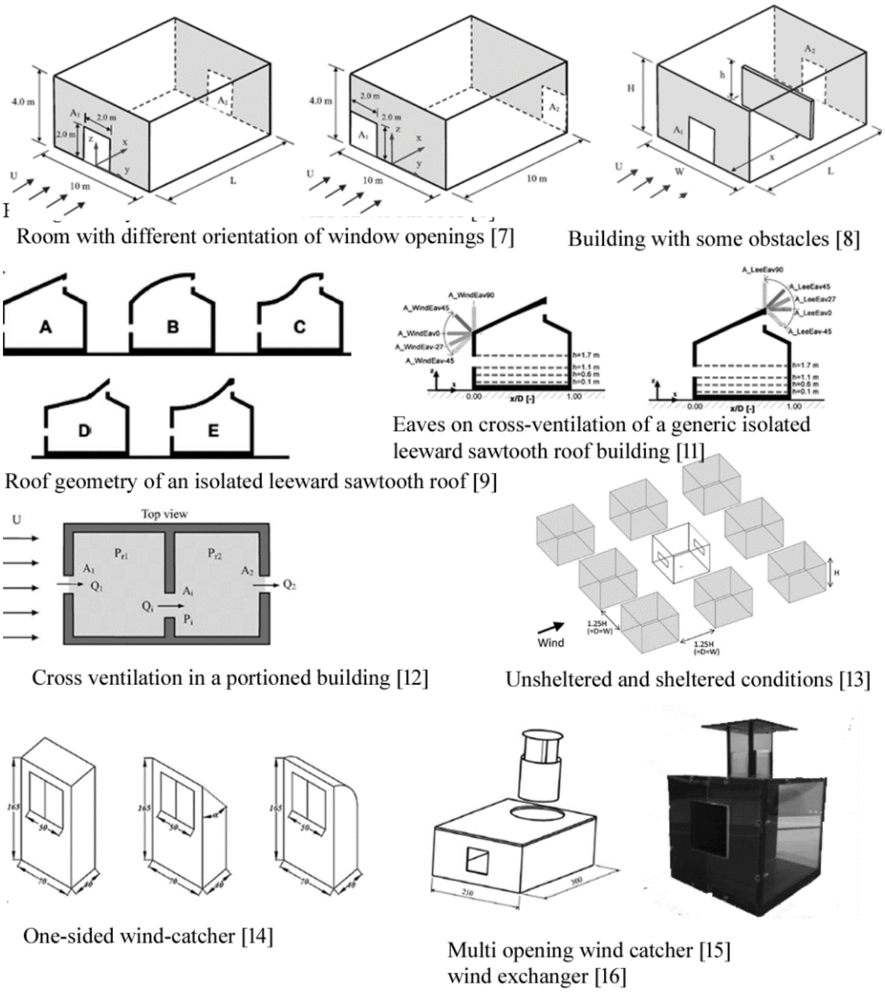


Fig. 2. Wind driven ventilation enhancement techniques.

Chu et al. [12] studied the wind cross ventilation in a portioned building and identified that the internal partitions reduce the difference between external and internal pressure and the ventilation rate of partitioned buildings is always smaller than that of buildings without partition. Tominaga and Blocken [13] studied the cross-ventilation flow of a generic building with contaminant dispersion in unsheltered and sheltered conditions. The air flow rate is reduced to 30% for the sheltered building due to the presence of the surrounding buildings.

Dehghan et al. [14] employed the one-sided wind-catcher and investigated the influence of wind speed and its direction on the ventilation capacity and identified that the wind-catcher with curved roof exhibits superior performance at zero wind incident angle. Montazeri [15] investigated the multi opening wind catcher and identified that the number of openings is a main factor in performance of wind catcher systems. The sensitivity of the performance of different wind catchers related to the wind angle decreases by increasing the number of openings.

Cruz-Salas et al. [16] investigated the natural ventilation of a room with wind exchanger and found that, the performance of a wind exchanger strongly depends on the orientation of its openings to the wind.

2.2. Buoyancy driven ventilation

Buoyancy driven ventilation occurs due to difference in density between internal and external air, which in turn due to temperature differences between inside and outside. This phenomenon is also referred as stack effect or chimney effect. The difference in density creates the pressure difference that pulls air in and out of the building through the openings in the building envelope.

Yusoff et al. [17] used the solar induced ventilation as a feasible alternative to improve stack ventilation. This study includes the roof solar collector and a vertical stack, in enhancing the stack ventilation performance in the hot and humid climate. The highest air temperature difference between the air inside the stack and the ambient air is achieved in the semi-clear sky condition and overcast sky condition is about 9.9°C and 6.2 °C respectively. Wang et al. [18] investigated the natural ventilation through multiple stack system. Imran [19] induced the flow for ventilation and cooling by solar chimney. It is observed that solar chimney induces ventilation to 50-425m^3/h for a room of 12m^3. Also, the air flow increases linearly with increases in solar radiation and with increase in the gap thickness between absorber and glass cover.

Rabani [20], experimentally studied a new trombe wall in combination with solar chimney and water spraying system in a test room under Yazd (Iran) desert climate. The results showed that the stored energy of the trombe wall plays important role in the air ventilation during non-sunny periods and the water spraying system enhances the thermal efficiency by approximately 30%. He et al. [21] studied the thermal behaviour of trombe wall system with venetian blind. The buildings integrated with the VBTW reduce heating energy needs and also achieves an acceptable condition of comfort in cold weather.

Shuli Liu, Yongcai Li [22] experimentally studied the thermal performance of a solar chimney with and without phase change material (PCM). For the case of solar chimney with PCM, three different modes (closed-fully charging mode, open-partly charging mode and open-fully charging mode) were developed. Shahreza and Imani [23] employed two intensifiers to intensify the heat flux radiated by the sun all around the solar chimney.

In the hybrid ventilation both natural ventilation and mechanical ventilation components are integrated to create a high efficiency and healthy ventilation system for a building. Figure 3 shows some the techniques to enhance buoyancy driven ventilation.

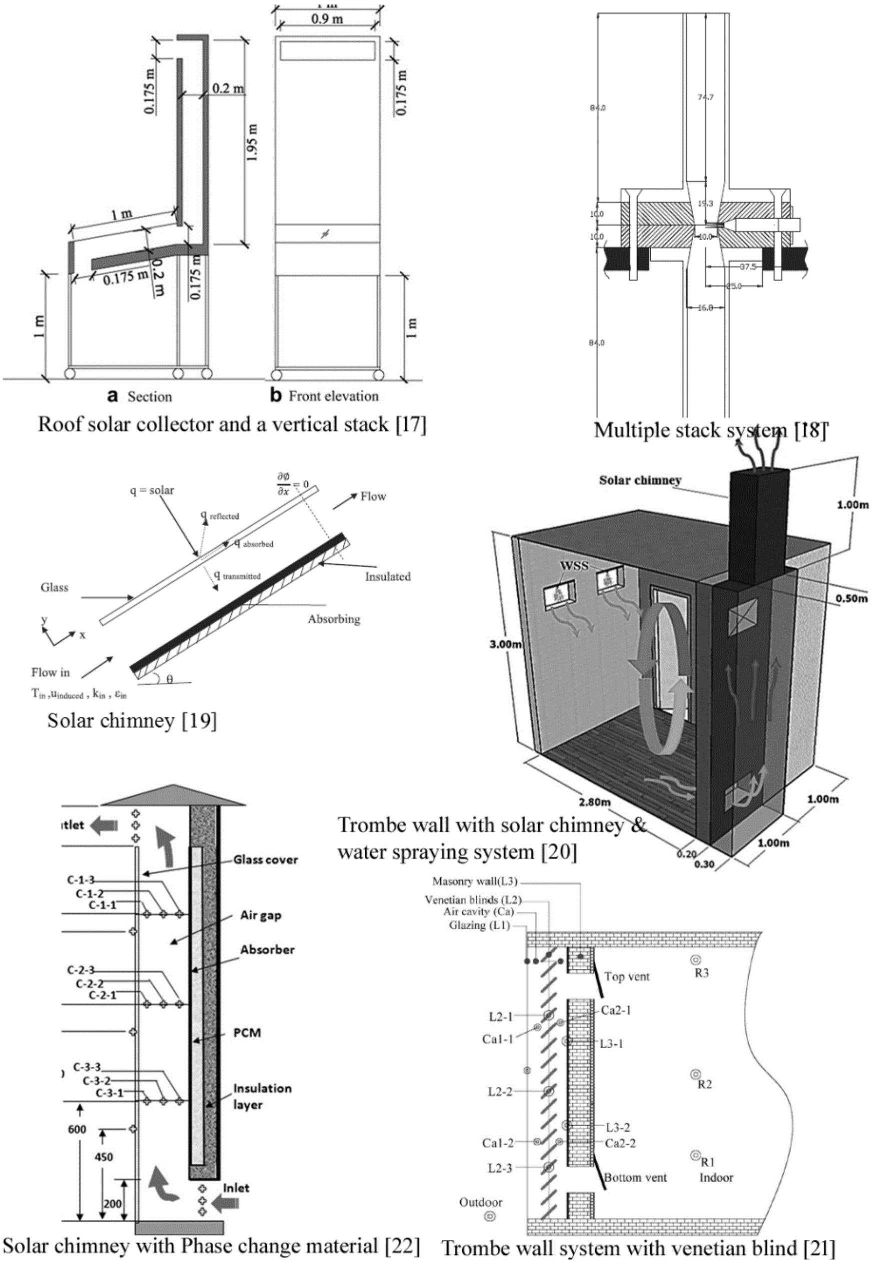


Fig. 3. Techniques to enhance Buoyancy driven ventilation.

3. Natural cooling

Natural cooling involves the use of natural processes for cooling the building to achieve the balanced interior conditions. Maintaining a comfortable environment within a building in a hot climate relies on reducing the rate of heat gains into the building and encouraging the removal of excess heat from the building. This section includes the review on broad categories of natural cooling techniques.

3.1. Evaporative cooling

Water on the surface of a building has a tendency to evaporate and helps to cool buildings, reducing the energy needed for air conditioning. Evaporative cooling combined with other passive design techniques provide adequate thermal comfort without air conditioning system. Evaporative cooling is categorized as passive direct cooling, passive indirect cooling, direct evaporative cooling and indirect evaporative cooling.

In the passive direct cooling system, fountains, sprays, pools and ponds are used. Direct evaporative coolers are commonly used in residential buildings and in this type, the reduction of temperature is followed by an increase of moisture content. However, in the indirect system, no moisture is added to the supply air stream. Evaporative cooling is used extensively for medium to low humidity climate.

Elgendy et al. [24] enhances the performance of a desiccant evaporative cooling system using direct/indirect evaporative cooler. Direct/indirect evaporative cooler after the rotating heat exchanger leads to increase the thermal and air handling COP. However, using it before the rotating heat exchanger increases the space cooling capacity and air handling capacity. Ali et al. [25] investigated the performance of solid desiccant evaporative cooling system configurations in different climatic zones.

Buker [26] did the experimental investigation of a building integrated photovoltaic/thermal roof collector combined with a liquid desiccant enhanced indirect evaporative cooling system. The experimental results show that the proposed tri-generation system is capable of providing about 3 kW of heating, 5.2 kW of cooling power and 10.3 MWh/year power generation, respectively.

Taleb [27] used passive cooling strategies to improve thermal performance and reduce energy consumption of residential buildings. This paper includes louver shading devices, double glazing, wind catcher, greenroofing, insulation, evaporative cooling via fountain, indirect radiant cooling, light colour coatings with high reflection. Davis and Hirmer [28] investigates the use of vertical gardens as evaporative coolers.

Nasrabadi and Finn [29] analysed the performance of a low approach low temperature direct cooling tower for high-temperature building cooling systems. The results show the low approach low temperature cooling tower has marginally better performance, but this difference is more pronounced at off peak cooling demand periods. Chen et al. [30], employed the passive evaporative cooling wall constructed of porous ceramic pipes with water sucking ability. This passive evaporative cooling wall is suitable for dry and hot climates or locations like semi-enclosed spaces in parks, pedestrian areas and residential courtyards and it is not suitable for the extreme humid climate and locations with a shortage of water for evaporation. Figure 4 shows some of the evaporative cooling techniques.

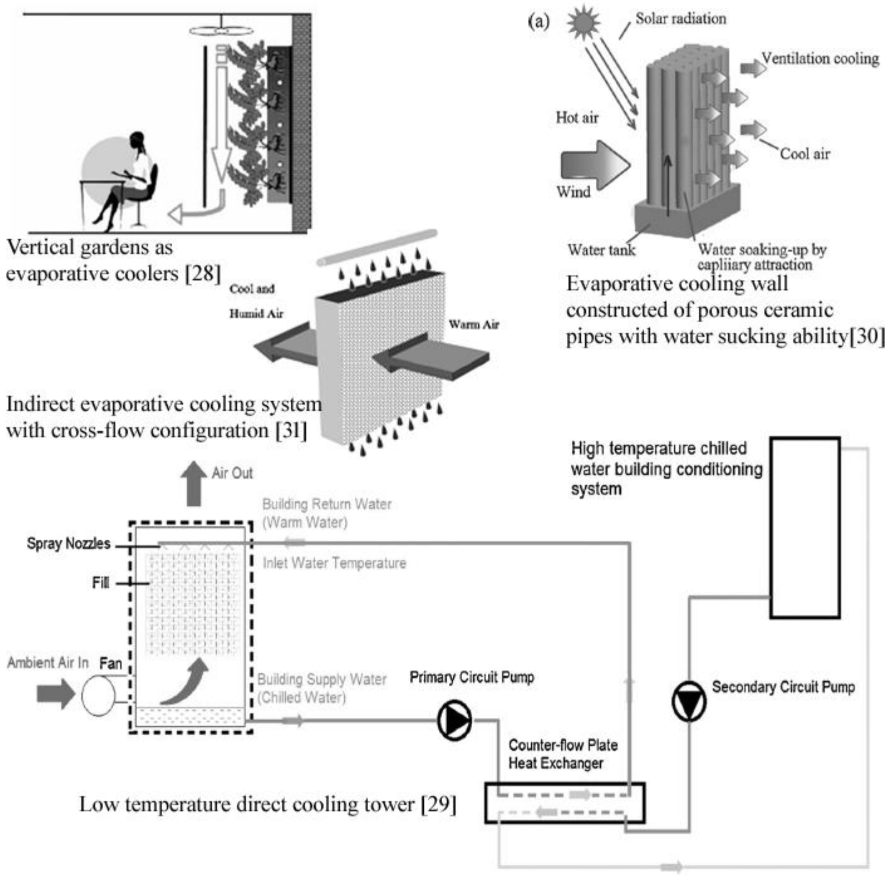
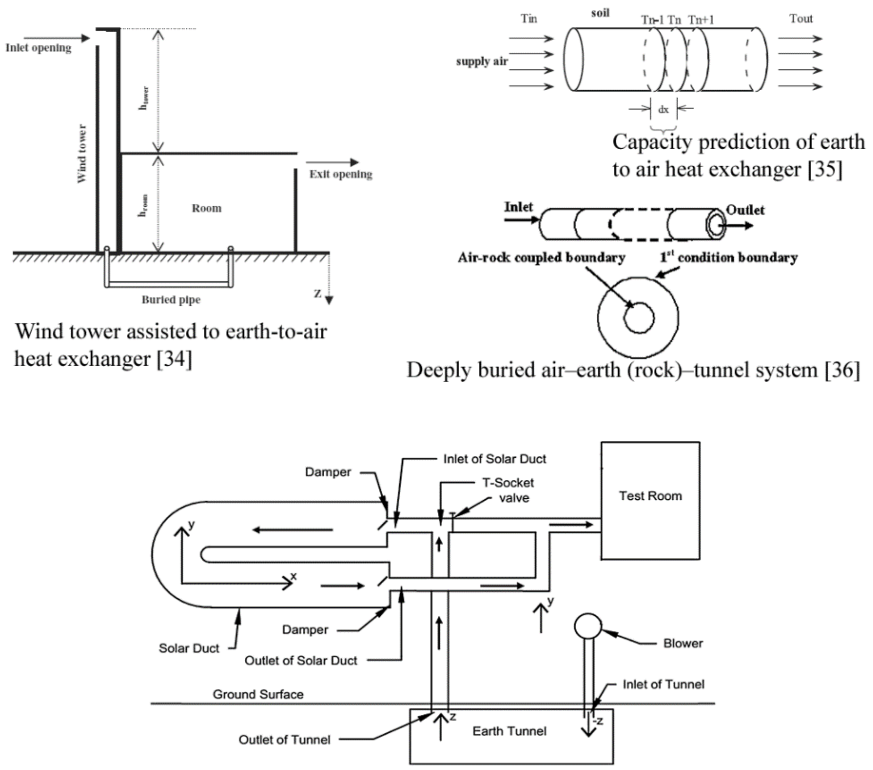


Fig. 4. Evaporative cooling techniques.

Heidarinejad and Moshari [31] modelled an indirect evaporative cooling system with cross-flow configuration. The numerical results of this study show the applicability of the model for both sub-and above-wet bulb cooling applications of buildings. Haghighi et al. [32] studied the vaulted roof assisted evaporative cooling channel for natural cooling of 1-floor building. The results also reveal that in regions with higher ambient air temperature, the thermal comfort is achieved only for less relative humidity values of the ambient air. Moreover, in regions with higher relative humidity values, naturally ventilated buildings should be insulated well.

3.2. Ground cooling

Soil temperature at a depth of 2–3 m is almost constant throughout the year and this temperature is higher than the outside temperature during the cold seasons and lower than the outside temperature in hot seasons [33]. Benhammou et al. [34] used the wind tower assisted to earth-to-air heat exchanger for passive cooling of buildings in arid and hot climate. Figure 5 shows the ground cooling techniques.



Wind tower assisted to earth-to-air heat exchanger [34]

Capacity prediction of earth to air heat exchanger [35]

Deeply buried air–earth (rock)–tunnel system [36]

Earth air tunnel heat exchanger coupled with a solar air heating duct [40]

Fig. 5. Ground cooling techniques.

Niu et al. [35] conducted performance analysis on heat and mass transfer and predicted cooling capacity of earth to air heat exchanger. This study includes six factors, namely the air temperature, the air relative humidity, the air velocity at the inlet of EAHE, the tube surface temperature, and the tube length and diameter on the performance were analyzed using the calibrated model. Su et al. [36] developed a numerical simulating model for the deeply buried air–earth (rock)–tunnel system and the simulated model have the maximum error 1.4 ◦C and 10% for air temperature and relative humidity respectively.

Misra et al. [37] investigated the thermal performance of hybrid earth air tunnel heat exchanger. EAHE coupled to the air-cooled condenser is an efficient, reliable and cost-effective method to increase the performance of any vapour compression refrigeration system such as window type air-conditioners which have wide spread application. Sarbu and Sebarchievici [38] discussed various types of ground source heat pumps and identified that vertical GSHP system has attracted the greatest interest in research field and practical engineering. Xamán et al. [39] studied the effect of thermal insulation on earth-to-air heat exchanger by numerical study and observed that insulation increased the heating effect up to 2◦C with respect to the EAHE without insulation. Jakhar et al. [40] investigated the performance of earth air tunnel heat exchanger coupled with a solar air heating duct and identified that the heating capacity of EATHE can be significantly increased by coupling it with solar air heating duct.

Do et al. [41] simulated the parametric analysis on performance of residential air-source heat pump (ASHP) system model with and without closed-loop EAHE. The EAHE system provides annual cooling energy savings of about 9.6% for Houston and13.8% for Dallas. Sanusi et al. [42] improved the ground cooling by earth pipe cooling technology. Li et al. [43] investigated an innovative passive air conditioning system coupling earth-to-air heat exchangers (EAHEs) with solar collector enhanced solar chimneys. During the natural airflow mode, it is found that the increase in the outdoor air temperature and solar radiation increases the solar chimney natural draft and the amount of airflow to the building, which in turn increases the amount of cooling capacity provided to the building.

3.3. Radiative cooling-roof cool paints

Roof coated with thermally reflective material reduces heat transfer through the coating and 90% of solar infrared radiation and 85% of ultraviolet radiation being radiated back from the coated surface. The first generation of materials used in cool roofs consisted of natural while the second generation was based on the development of artificial white materials designed to present very high albedo and third phase is the development of colored high reflective materials [44].

Pisello et al. [45] performed an experimental analysis of a combined albedo measurement campaign for the characterization of an innovative water proof polyurethane-based membrane for cool roof application. Cozza et al. [46] did the research to formulate exterior building paints as smart coatings with high IR-reflectance to decrease the use of energy for cooling buildings

Raj et al. [47] developed pigments based on terbium-doped yttrium created with high NIR reflectance for cool roof and surface coating applications. Yew et al. [48] focused on a TIC integrated with a series of aluminium tubes that are installed on the underside of the metal roof. Gagliano et al. [49] compared the energy and environmental behaviour of cool, green and traditional roofs and identified that green and cool roofs provide higher energy savings and environmental benefits than highly insulated standard roofs.

Uemoto et al. [50] investigated the thermal performance of cool colored acrylic paints containing infrared reflective pigments in comparison to conventional colored acrylic paints of similar colors (white, brown and yellow) applied on sheets of corrugated fiber cement roofing. Romeo and Zinzi [51] studied the impact of a cool roof application on the energy and comfort performance in an existing non-residential building. The study registered a 54% reduction of the cooling energy demand and cool roof resulted as the most efficient among the different cooling efficient technologies considered for the comparison. Ali Akbar Azematia et al. [52] used mineral insulator in paints for energy saving. The results showed that the coating with mineral particles has an important role in the thermal insulation and leads to a 17% decrease in energy consumption. Ferrari et al. [53] tested the achieve roof tiles with high capacity of rejecting solar radiation. It consists of using a cool-colored tile with relatively high solar reflectance, combined with a thin insulating layer attached below the tile and made of a silica-gel super-insulating material. Kinoshita and Yoshida [54] made a performance analysis and optimizes the spectral solar reflectance of cool painted layers. Dias et al. [55] studied the impact of cool paints using on energy demand and thermal comfort of a residential building. The role of the cool paints during an especially hot summer period is really dramatic and a maximum reduction of 5 °C was observed, from 28.0 °C to 23.0 °C, which is an acceptable indoor temperature in Portugal. American Roof tile Coatings and Lawrence Berkeley National Laboratory identified that the new coloured pigments significantly reduce surface temperature, which consequently reduce the necessity for cooling energy in buildings with and without air-conditioning systems [56]. Total reflectance value of some cool roof paints is given in Table 1.

Table 1. Total reflectance of conventional and cool roof paints [57].

Paint	Total reflectance %	Paint	Total reflectance %
Cool white	77.9	Conventional brown	30.2
Conventional white	65.5	Cool yellow	67.9
Cool brown	61.9	Conventional yellow	42.8

3.4. Solar insulation material for roof

Insulation materials are the key tool in designing and constructing an energy thrifty buildings. The use of insulation materials has increased, both in terms of buildings being insulated and in the minimum values of insulation required by the national regulations. Insulating materials can be classified according to their chemical or their physical structure. The most widely used insulating materials can accordingly be classified as inorganic, organic, combined material and sustainable materials. Some of the commonly used roof insulation material and its properties are given in Table 2.

Table 2. Commonly used roof insulation materials.

Material	Embodied energy MJ/kg	Density kg/m^3	Thermal conductivity W/mK
Mineral wool [58]	16.6	16	0.038
Rock wool [58]	16.8	23	0.037
Cork [58]	4	110	0.040
Fibreglass [58]	28	24	0.036
Polystyrene [58]	86.4	16	0.037
Polyurethane [58]	101.5	24	0.028
Expanded Polystyrene[59]	-	15 [60]	0.037

Tettey et al. [61] studied the effects of different insulation materials from mineral rock wool to glass wool, cellulose fiber, expanded polystyrene or foam glass on primary energy and CO_2 emission for the building materials production of a multi-storey residential building. The results showed a reduction of about 6–7%in primary energy use and 6–8% in CO_2 emission when the insulation material in the reference buildings is changed from rock wool to cellulose fiber in the optimum versions. Also, the total fossil fuel use for the production of insulation material was reduced by 39%.

Mozumdera and Singh [62] studied the solar heat flux reduction through roof using fly ash as porous insulation layer. The experimental results demonstrate that the layer provides excellent insulation and it also shows structural stability.

Jim [63] used rock wool, polystyrene foam to study the air conditioning energy consumption in green roof buildings. Kumar and Suman [64] experimentally evaluated the impact of insulation materials for walls and roofs on indoor thermal comfort under composite climate. It is found that the wall with 50 mm elastospray insulation satisfies the ECBC requirements and for other insulation materials like PUF, EPS, Fiber glass and foam concrete, the required thicknesses is 60 mm, 70 mm, 80 mm and 150 mm, respectively, to satisfy the ECBC requirements. Similarly, in the conventional roof, 50 mm Elastospray insulation satisfies the ECBC requirements, whereas other insulation PUF, EPS, Fiber glass and foam concrete require thicknesses of 55 mm, 70 mm, 80 mm and 140 mm respectively to satisfy the recommended values.

Barletta et al. [65] employed environment friendly wooden-based coatings for thermal insulation. The coating is composed of two superimposed layers; the innermost layer consists of dried beech dust dispersed in a diluted polyurethane binder, while the outermost layer is a conventional decorative hybrid epoxy-polyester powder coating. The increased concentration of wood particles improved the thermal insulation properties of the coating material as a result of their low intrinsic conductivity and due to their capability to act as a discontinuity in the propagation of thermal energy across the coating.

Batouli et al. [66] performed a life cycle assessment of a kenaf-fiber reinforced polyurethane. Three composites made of rigid polyurethane (PU) reinforced with 5, 10 and 15 percent kenaf core were prepared and analyzed. It is shown that although kenaf has much less environmental impact than PU, increasing the amount of kenaf core in PU composites does not necessarily result in less environmental impact.

Patnaik et al. [67] studied the thermal and sound insulation of samples developed from waste wool and recycled polyester fibres (RPET) for building industry applications. Waste wool fibres were mixed with recycled polyester fibres in 50/50 proportions in the form of a two-layer mat. The RPET/waste wool mats were absorbing more than 70% incident noise in the frequency range of 50 - 5700 Hz and have adequate moisture resistance at high humidity conditions without affecting the insulation and acoustic properties. Also 65–70% biodegradation was achieved for wool/RPET mats for 50 days composting period.

Zhang et al. [68] investigated the thermal insulation properties of both domestic and wild silkworm cocoons under warm conditions. The thermal insulation properties of both domestic (B. mori and S. cynthia) and wild silkworm cocoons (A. pernyi and A. mylitta) were investigated and identified that wild cocoons exhibited a higher level of thermal buffer than the domestic ones

Briga-Sa et al. [69] studied the potential applicability of woven fabric waste (WFW) and a waste of this residue, named woven fabric subwaste (WFS), as thermal insulation building material. The obtained results show that the application of the WFW and WFS in the external double wall increases its thermal behaviour in 56% and 30%, respectively. The thermal conductivity value of the WFW is similar to the values obtain for expanded polystyrene (EPS), extruded polystyrene (XPS) and mineral wool (MW).

Paiva et al. [70] evaluated the thermal insulation performance of corn cob particleboards. The studied particleboard has shown a disappointingly low thermal insulating performance. Jorge Pinto et al. [71] found several similarities in corn cob with extruded polystyrene (XPS), expanded polystyrene (EPS), and suggested that the corn cob may be used as a raw material to process thermal insulating products, light partition walls, ceiling coating, indoor doors and furniture, among other possible applications.

Wei et al. [72] evaluated the performance of a new thermal insulation material from rice straw using high frequency hot-pressing. Increasing particle MC in a certain range can improve the mechanical properties of boards, but the higher particle moisture content could reduce the dimensional stability of RSTIB.

Korjenic et al. [73] developed a new insulating material using jute, flax, and hemp. Thermal insulations made from natural raw materials are likely to become a suitable alternative to commonly used boards made from different materials (mineral wool, polystyrene or polyurethane).

Kader et al. [74] evaluated the thermal insulation and mechanical properties of waste rubber/natural rubber composite. The addition of waste rubber leads to a slight increase in thermal conductivity and also leads to improvement of mechanical properties of composites. The optimum concentration which is 600 phr waste rubber loading agrees with the swelling and mechanical measurements which has desirable thermal insulation and high mechanical properties and decreases the cost of materials to 82% of the NR cost. Kymalainen and Sjoberg [75] evaluated the suitability of bast fibres of flax and hemp for thermal insulations. Bast fibres as a natural resource have a risk for microbial and other contaminants, and their quality should be monitored regularly. Careful procedures during harvesting, processing, manufacturing, building and maintenance of buildings are required in order to avoid the risk of negative effects (i.e. moulding) caused by moisture and free water. Panyakaew and Fotios [76] developed a new insulation board with coconut husk and bagasse and found that thermal conductivity of the coconut husk and bagasse insulation boards was measured according to ISO 8301 and this suggested that both insulation boards have thermal conductivity values ranging from 0.046 to 0.068W/mK which were close to those of conventional insulation materials such as cellulose fibres and mineral wool.

Da Rosa et al. [77] uses the rice husk and sunflower stalk as a substitute for glass wool in thermal insulation of solar collector**.** This board behaved in a similar way to glass wool, in terms of the function of thermal insulation in solar collectors for heating water. Zhou et al. [78] developed binderless cotton stalk fiber board (BCSF) made from cotton stalk fibers with no chemical additives was developed using high frequency hot pressing. The results showed that the board with a density of 150–450 kg/m^3 had the thermal conductivity values ranging from 0.0585 to 0.0815 W/m K, which was close to that of the expanded perlite and vermiculite within the same density range. Binici et al. [79] examined the usage of cotton waste, fly ash and epoxy resin on production of chipboards. It was proved that lightweight construction materials produced with cotton waste, fly ash and epoxy resin could be used for getting better thermal and sound insulation results. Benmansour et al. [80] studied the thermal and mechanical performance of natural mortar reinforced with date palm fibers (DPF) for use as insulating materials in building. The results reveal that the incorporation of DPF reduces the thermal conductivity and the compressive strength of the composite while reducing the weight. Figure 6 shows some of the sustainable roof insulation material with its thermal conductivity value.

Silkworm cocoons
***K* = 0.0106 W/m K to 0.0653 W/m K [68]**

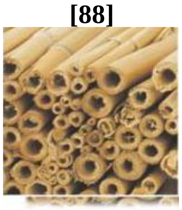
Cotton waste
***k* = 0.0022 kW/mK [79]**

Wovenfabric
***k* = 0.044W/m°C [69]**

Date palm fibe [80]
***k* =0.072–0.085 w/mk [88]**

Corncob
***k*= 0.101 W/m◦C [70]**

Strawbale *k*=0.13–0.19 W/m^2 K [82]

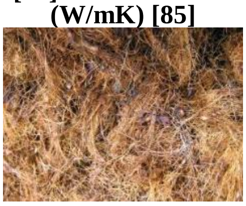


Reed [83] *k* =0.045-0.056 W/mK, [84]

Sugarcane baggase [83]. *k*=0.046–0.055 (W/mK) [85]

Hemp [73]
***k*=0.0458-0.039 W/mK, [73]**

Sunflower stalk [86]
***k* =0.0885-0.11 W/mK, [83]**



Palm fibre [83]
***k*= 0.15 and 0.17 W/mK [87]**

Fig. 6. Some sustainable roof insulation materials and its thermal conductivity *k* value.

Luamkanchanaphan et al. [81] studied the physical, mechanical and thermal Properties for thermal insulation from narrow-leaved cattail fibers. Thermal conductivity measured in accordance with the ASTM C518 revealed that the board with a density of 200-400 kg/m^3 had the thermal conductivity values ranging from 0.0438-0.0606 W/m K, which was less than that of fibrous materials and cellular materials.Thomson and Walker [82] reported that degradation behaviour of wheat straw cyclically exposed to elevated humidity levels. Straw may be able to withstand relatively high transient moisture contents without suffering serious decay is encouraging for the wider acceptance of this form of construction. Binici et al. [86] studied the mechanical and thermal conductivity property for sunflower stalk, textile waste and stubble fibres. Sunflower stem and gypsum blocks made with binder led to better thermal insulation in homes.

4. Conclusion

The present paper reviews some of the recent techniques adopted for passive cooling of buildings through heat dissipation approach. From this review, it is clearly observed that most of the research works get switch over from mechanical cooling and focussing towards the concept of green building through passive cooling. Many strategies are discussed in the passive cooling through natural ventilation and natural cooling concept. Among the reviewed techniques, cooling the building by using reflective paints and roof insulation layer is identified as the best method, since it controls the indoor temperature in an effective way. Also, the sustainable material like date palm, pecan, sunflower cake, reeds, hemp, and residue from sugarcane are identified as best material for thermal insulation.

References

1. Geetha, N.B.; and Velraj, R. (2012). Passive cooling methods for energy efficient buildings with and without thermal energy storage - A review. *Energy Education Science and Technology Part A: Energy Science and Research*, 29(2), 913-946.
2. BEE (2009). *Energy conservation building code user guide*. Bureau of Energy Efficiency, New Delhi.
3. Hummelgaard, J.; Juhl, P.; Sæbjörnsson, K.O.; Clausen, G.; Toftum, J.; and Langkilde, G. (2007). Indoor air quality and occupant satisfaction in five mechanically and four naturally ventilated open-plan office buildings. *Building and Environment*, 42(12), 4051-4058.
4. Sadineni, S.B.; Madala, S.; and Boehm, R.F. (2011). Passive building energy savings: A review of building envelope components. *Renewable and Sustainable Energy Reviews*, 15(8), 3617-3631.
5. CIBSE (1997). Natural ventilation in non-domestic buildings: applications manual 10, AM10. London: Chartered Institution of Building Services Engineers (CIBSE).
6. Mumovic, D.; Santamouris, M. (2009). A handbook of sustainable building design and engineering: an integrated approach to energy, health and operational performance. England: Earthscan.
7. Chu, C.-R.; and Chiang, B.F. (2014). Wind-driven cross ventilation in long buildings. *Building and Environment*, 80, 150-158.
8. Chu, C.R.; and Chiang, B.-F. (2013). Wind-driven cross ventilation with internal obstacles. *Energy and Buildings*, 67, 201-209.

9. Peren, J.I.; van Hooff, T.; Ramponi, R.; Blocken, B.; and Leite, B.C.C. (2015). Impact of roof geometry of an isolated leeward sawtooth roof building on cross-ventilation: Straight, concave, hybrid or convex. *Journal of Wind Engineering and Industrial Aerodynamics*, 145, 102-114.
10. Lo, L.J.; and Novoselac, A. (2012). Cross ventilation with small openings: Measurements in a multi-zone test building. *Building and Environment*, 57, 377-386.
11. Peren, J.I.; van Hooff, T.; Leite, B.C.C.; and Blocken, B. (2015). Impact of eaves on cross-ventilation of a generic isolated leeward sawtooth roof building: windward eaves, leeward eaves and eaves inclination. *Building and Environment,* 92, 578-590.
12. Chu, C.R.; Chiu, Y.H.; and Wang, Y.W. (2010). An experimental study of wind-driven cross ventilation in partitioned buildings. *Energy and Buildings*, 42(5), 667-673.
13. Tominaga, Y.; and Blocken, B. (2015). Wind tunnel experiments on cross-ventilation flow of a generic building with contaminant dispersion in unsheltered and sheltered conditions. *Building and Environment,* 92, 452-461.
14. Dehghan, A.A.; Esfeh, M.K.; and Manshadi, M.D. (2013). Natural ventilation characteristics of one-sided wind catchers: experimental and analytical evaluation. *Energy and Buildings*, 61, 366-377.
15. Montazeri, H. (2011). Experimental and numerical study on natural ventilation performance of various multi-opening wind catchers. *Building and Environment*,46(2), 370-378.
16. Cruz-Salas, M.V.; Castillo, J.A.; and Huelsz, G. (2014). Experimental study on natural ventilation of a room with a windward window and different windexchangers. *Energy and Buildings*, 84, 458-465.
17. Yusoff, W.F.M.; Salleh, E.; Adam, N.M.; Sapian, A.R.; and Sulaiman, M.Y. (2010). Enhancement of stack ventilation in hot and humid climate using a combination of roof solar collector and vertical stack. *Building and Environment*, 45(10), 2296-2308.
18. Wang, B.; Etheridge, D.W.; and Ohba, M. (2011). Wind tunnel investigation of natural ventilation through multiple stacks. Part 2: Instantaneous values.*Building and Environment*, 46(7), 1393-1402.
19. Imran, A.A.; Jalil, J.M.; and Ahmed, S.T. (2015). Induced flow for ventilation and cooling by a solar chimney. *Renewable Energy*, 78, 236-244.
20. Rabani, M.; Kalantar, V.; Dehghan, A.A.; and Faghih, A.K. (2015). Empirical investigation of the cooling performance of a new designed Trombe wall in combination with solar chimney and water spraying system. *Energy and Buildings,* 102, 45-57.
21. He, W.; Hu, Z.; Luo, B.; Hong, X.; Sun, W.; and Ji, J. (2015). The thermal behavior of Trombe wall system with venetian blind: An experimental and numerical study. *Energy and Buildings,* 104, 395-404.
22. Li, Y.; and Liu, S. (2014). Experimental study on thermal performance of a solar chimney combined with PCM. *Applied Energy*, 114, 172-178.
23. Shahreza, A.R.; and Imani, H. (2015). Experimental and numerical investigation on an innovative solar chimney. *Energy Conversion and Management*, 95, 446-452.

24. Elgendy, E.; Mostafa, A.; and Fatouh, M. (2015). Performance enhancement of a desiccant evaporative cooling system using direct/indirect evaporative cooler.*International Journal of Refrigeration*, 51, 77-87.
25. Ali, M.; Vukovic, V.; Sheikh, N.A.; and Ali, H.M. (2015). Performance investigation of solid desiccant evaporative cooling system configurations in different climatic zones. *Energy Conversion and Management*, 97, 323-339.
26. Buker, M.S.; Mempouo, B.; and Riffat, S.B. (2015). Experimental investigation of a building integrated photovoltaic/thermal roof collector combined with a liquid desiccant enhanced indirect evaporative cooling system. *Energy Conversion and Management*, 101, 239-254.
27. Taleb, H.M. (2014). Using passive cooling strategies to improve thermal performance and reduce energy consumption of residential buildings in UAE buildings. *Frontiers of Architectural Research*, 3(2), 154-165.
28. Davis, M.M.; and Hirmer, S. (2015). The potential for vertical gardens as evaporative coolers: An adaptation of the 'Penman Monteith Equation'. *Building and Environment*, 92, 135-141.
29. Nasrabadi, M.; and Finn, D.P. (2014). Performance analysis of a low approach low temperature direct cooling tower for high-temperature building cooling systems. *Energy and Buildings*, 84, 674-689.
30. Chen, W.; Liu, S.; and Lin, J. (2015). Analysis on the passive evaporative cooling wall constructed of porous ceramic pipes with water sucking ability. *Energy and Buildings*, 86, 541-549.
31. Heidarinejad, G.; and Moshari, S. (2015). Novel modeling of an indirect evaporative cooling system with cross-flow configuration. *Energy and Buildings*, 92, 351-362.
32. Haghighi, A.P.; Golshaahi, S.S.; and Abdinejad, M. (2015). A study of vaulted roof assisted evaporative cooling channel for natural cooling of 1-floor buildings. *Sustainable Cities and Society*, 14, 89-98.
33. Hammond, G.P.; and Jones, C.I. (2008). Embodied energy and carbon in construction materials. *Proceedings of the Institution of Civil Engineers-Energy*,161(2), 87-98.
34. Benhammou, M.; Draoui, B.; Zerrouki, M.; and Marif, Y. (2015). Performance analysis of an earth-to-air heat exchanger assisted by a wind tower for passive cooling of buildings in arid and hot climate. *Energy Conversion and Management*, 91, 1-11.
35. Niu, F.; Yu, Y.; Yu, D.; and Li, H. (2015). Heat and mass transfer performance analysis and cooling capacity prediction of earth to air heat exchanger. *Applied Energy*, 137, 211-221.
36. Su, H.; Liu, X. B.; Ji, L.; and Mu, J.Y. (2012). A numerical model of a deeply buried air–earth–tunnel heat exchanger. *Energy and Buildings*, 48, 233-239.
37. Misra, R.; Bansal, V.; Agarwal, G.D.; Mathur, J.; and Aseri, T. (2012). Thermal performance investigation of hybrid earth air tunnel heat exchanger. *Energy and Buildings*, 49, 531-535.
38. Sarbu, I.; and Sebarchievici, C. (2014). General review of ground-source heat pump systems for heating and cooling of buildings. *Energy and Buildings*, 70, 441-454.

39. Xamán, J.; Hernández-Pérez, I.; Arce, J.; Álvarez, G.; Ramírez-Dávila, L.; and Noh-Pat, F. (2014). Numerical study of earth-to-air heat exchanger: The effect of thermal insulation. *Energy and Buildings*, 85, 356-361.
40. Jakhar, S.; Misra, R.; Bansal, V.; and Soni, M.S. (2015). Thermal performance investigation of earth air tunnel heat exchanger coupled with a solar air heating duct for northwestern India. *Energy and Buildings*, 87, 360-369.
41. Do, S.L.; Baltazar, J.C.; and Haberl, J. (2015). Potential cooling savings from a ground-coupled return-air duct system for residential buildings in hot and humid climates. *Energy and Buildings*, 103, 206-215.
42. Sanusi, A.N.; Shao, L.; and Ibrahim, N. (2013). Passive ground cooling system for low energy buildings in Malaysia (hot and humid climates). *Renewable Energy*, 49, 193-196.
43. Li, H.; Yu, Y.; Niu, F.; Shafik, M.; and Chen, B. (2014). Performance of a coupled cooling system with earth-to-air heat exchanger and solar chimney. *Renewable Energy*; 62, 468-477
44. Santamouris, M. (2014). Cooling the cities–a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Solar Energy*, 103, 682-703.
45. Pisello, A.L.; Castaldo, V.L.; Pignatta, G.; Cotana, F.; and Santamouris, M. (2015). Experimental in-lab and in-field analysis of waterproof membranes for cool roof application and urban heat island mitigation. *Energy and Buildings*, 114, 180-190.
46. Cozza, E.S.; Alloisio, M.; Comite, A.; Di Tanna, G.; and Vicini, S. (2015). NIR-reflecting properties of new paints for energy-efficient buildings. *Solar Energy*,116, 108-116.
47. Raj, A.K.; Rao, P.P.; Sameera, S.; and Divya, S. (2015). Pigments based on terbium-doped yttrium cerate with high NIR reflectance for cool roof and surface coating applications. *Dyes and Pigments*, 122, 116-125.
48. Yew, M.C.; Sulong, N.R.; Chong, W.T.; Poh, S.C.; Ang, B.C.; and Tan, K.H. (2013). Integration of thermal insulation coating and moving-air-cavity in a cool roof system for attic temperature reduction. *Energy Conversion and Management*, 75, 241-248.
49. Gagliano, A.; Detommaso, M.; Nocera, F.; and Evola, G. (2015). A multi-criteria methodology for comparing the energy and environmental behavior of cool, green and traditional roofs. *Building and Environment*, 90, 71-81.
50. Uemoto, K.L.; Sato, N.M.; and John, V.M. (2010). Estimating thermal performance of cool colored paints. *Energy and Buildings*, 42(1), 17-22.
51. Romeo, C.; and Zinzi, M. (2013). Impact of a cool roof application on the energy and comfort performance in an existing non-residential building. A Sicilian case study. *Energy and Buildings*, 67, 647-657.
52. Azemati, A.A.; Hadavand, B.S.; Hosseini, H.; and Tajarrod, A.S. (2013). Thermal modeling of mineral insulator in paints for energy saving. *Energy and Buildings*, 56, 109-114.
53. Ferrari, C.; Libbra, A.; Cernuschi, F.M.; De Maria, L.; Marchionna, S.; Barozzi, M.; and Muscio, A. (2015). A composite cool colored tile for sloped roofs with high 'equivalent'solar reflectance. *Energy and Buildings*, 114, 221-226.

54. Kinoshita, S.; and Yoshida, A. (2015). Investigating performance prediction and optimization of spectral solar reflectance of cool painted layers. *Energy and Buildings*, 114, 214-220.
55. Dias, D.; Machado, J.; Leal, V.; and Mendes, A. (2014). Impact of using cool paints on energy demand and thermal comfort of a residential building. *Applied Thermal Engineering*, 65(1), 273-281.
56. Al-Obaidi, K.M.; Ismail, M.; and Rahman, A.M.A. (2014). Passive cooling techniques through reflective and radiative roofs in tropical houses in Southeast Asia: A literature review. *Frontiers of Architectural Research*, 3(3), 283-297.
57. Uemoto, K.L.; Sato, N.M.; and John, V.M. (2010). Estimating thermal performance of cool colored paints. *Energy and Buildings*, 42(1), 17-22.
58. Hammond, G.P.; and Jones, C.I. (2008). Embodied energy and carbon in construction materials. *Proceedings of the Institution of Civil Engineers-Energy*, 161(2), 87-98.
59. Tong, S.; Li, H.; Zingre, K.T.; Wan, M.P.; Chang, V.W.C.; Wong, S.K.; and Lee, I.Y.L. (2014). Thermal performance of concrete-based roofs in tropical climate. *Energy and Buildings*, 76, 392-401.
60. Pargana, N.; Pinheiro, M.D.; Silvestre, J.D.; and de Brito, J. (2014). Comparative environmental life cycle assessment of thermal insulation materials of buildings. *Energy and Buildings*, 82, 466-481.
61. Tettey, U.Y.A.; Dodoo, A.; and Gustavsson, L. (2014). Effects of different insulation materials on primary energy and CO 2 emission of a multi-storey residential building. *Energy and Buildings*, 82, 369-377.
62. Mozumder, A.; and Singh, A.K. (2012). Solar heat flux reduction through roof using porous insulation layer. *Energy Procedia*, 30, 446-451.
63. Jim, C.Y. (2014). Air-conditioning energy consumption due to green roofs with different building thermal insulation. *Applied Energy*, 128, 49-59.
64. Kumar, A.; and Suman, B.M. (2013). Experimental evaluation of insulation materials for walls and roofs and their impact on indoor thermal comfort under composite climate. *Building and Environment*, 59, 635-643.
65. Barletta, M.; Guarino, S.; Rubino, G.; Trovalusci, F.; and Tagliaferri, V. (2014). Environmentally friendly wooden-based coatings for thermal insulation: Design, manufacturing and performances. *Progress in Organic Coatings*, 77(3), 701-711.
66. Batouli, S.M.; Zhu, Y.; Nar, M.; and D'Souza, N.A. (2014). Environmental performance of kenaf-fiber reinforced polyurethane: a life cycle assessment approach. *Journal of Cleaner Production*, 66, 164-173.
67. Patnaik, A.; Mvubu, M.; Muniyasamy, S.; Botha, A.; and Anandjiwala, R.D. (2015). Thermal and sound insulation materials from waste wool and recycled polyester fibers and their biodegradation studies. *Energy and Buildings*, 92, 161-169.
68. Zhang, J.; Rajkhowa, R.; Li, J.L.; Liu, X.Y.; and Wang, X.G. (2013). Silkworm cocoon as natural material and structure for thermal insulation. *Materials and Design*, 49, 842-849.

69. Briga-Sá, A.; Nascimento, D.; Teixeira, N.; Pinto, J.; Caldeira, F.; Varum, H.; and Paiva, A. (2013). Textile waste as an alternative thermal insulation building material solution. *Construction and Building Materials*, 38, 155-160.
70. Paiva, A.; Pereira, S.; Sá, A.; Cruz, D.; Varum, H.; and Pinto, J. (2012). A contribution to the thermal insulation performance characterization of corn cob particleboards. *Energy and Buildings*, 45, 274-279.
71. Pinto, J.; Cruz, D.; Paiva, A.; Pereira, S.; Tavares, P.; Fernandes, L.; and Varum, H. (2012). Characterization of corn cob as a possible raw building material. *Construction and Building Materials*, 34, 28-33.
72. Wei, K.; Lv, C.; Chen, M.; Zhou, X.; Dai, Z.; and Shen, D. (2015). Development and performance evaluation of a new thermal insulation material from rice straw using high frequency hot-pressing. *Energy and Buildings*, 87, 116-122.
73. Korjenic, A.; Petránek, V.; Zach, J.; and Hroudová, J. (2011). Development and performance evaluation of natural thermal-insulation materials composed of renewable resources. *Energy and Buildings*, 43(9), 2518-2523.
74. Kader, M.A.; Abdel-wehab, S.M.; Helal, M.A.; and Hassan, H.H. (2012). Evaluation of thermal insulation and mechanical properties of waste rubber/natural rubber composite. *HBRC Journal*, 8(1), 69-74.
75. Kymäläinen, H.R.; and Sjöberg, A.M. (2008). Flax and hemp fibres as raw materials for thermal insulations. *Building and environment*, 43(7), 1261-1269.
76. Panyakaew, S.; and Fotios, S. (2011). New thermal insulation boards made from coconut husk and bagasse. *Energy and buildings*, 43(7), 1732-1739.
77. da Rosa, L.C.; Santor, C.G.; Lovato, A.; da Rosa, C.S.; and Güths, S. (2015). Use of rice husk and sunflower stalk as a substitute for glass wool in thermal insulation of solar collector. *Journal of Cleaner Production*, 104, 90-97.
78. Zhou, X.Y.; Zheng, F.; Li, H.G.; and Lu, C.L. (2010). An environment-friendly thermal insulation material from cotton stalk fibers. *Energy and Buildings*, 42(7), 1070-1074.
79. Binici, H.; Gemci, R.; Kucukonder, A.; and Solak, H.H. (2012). Investigating sound insulation, thermal conductivity and radioactivity of chipboards produced with cotton waste, fly ash and barite. *Construction and Building Materials*, 30, 826-832.
80. Benmansour, N.; Agoudjil, B.; Gherabli, A.; Kareche, A.; and Boudenne, A. (2014). Thermal and mechanical performance of natural mortar reinforced with date palm fibers for use as insulating materials in building. *Energy and Buildings*, 81, 98-104.
81. Luamkanchanaphan, T.; Chotikaprakhan, S.; and Jarusombati, S. (2012). A study of physical, mechanical and thermal properties for thermal insulation from narrow-leaved cattail fibers. *APCBEE Procedia*, 1, 46-52.
82. Thomson, A.; and Walker, P. (2014). Durability characteristics of straw bales in building envelopes. *Construction and Building Materials, 68*, 135-141.
83. Asdrubali, F.; D'Alessandro, F.; and Schiavoni, S. (2015). A review of unconventional sustainable building insulation materials. *Sustainable Materials and Technologies*, 4, 1-17.
84. Tom Hisss. (2003). Retrieved June, 2003, from http://www.hiss-reet.de.

85. Manohar, K.; Ramlakhan, D.; Kochhar, G.; and Haldar, S. (2006). Biodegradable fibrous thermal insulation. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 28(1), 45-47.
86. Binici, H.; Eken, M.; Dolaz, M.; Aksogan, O.; and Kara, M. (2014). An environmentally friendly thermal insulation material from sunflower stalk, textile waste and stubble fibres. *Construction and Building Materials*, 51, 24-33.
87. Chikhi, M.; Agoudjil, B.; Boudenne, A.; and Gherabli, A. (2013). Experimental investigation of new biocomposite with low cost for thermal insulation. *Energy and Buildings*, 66, 267-273.
88. Agoudjil, B.; Benchabane, A.; Boudenne, A.; Ibos, L.; and Fois, M. (2011). Renewable materials to reduce building heat loss: Characterization of date palm wood. *Energy and buildings*, 43(2), 491-497.