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Quantifying the Contribution of Deep Bioclimatic Design to the Sustainable Level of Buildings in Warm Climates

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Abstract: This study examines the contribution of *deep bioclimatic design* to the overall sustainability performance of buildings in warm climates. To this end, the sustainability scores of a house designed according to deep bioclimatic principles were compared with those of a conventionally designed building using 11 of the most widely recognized GBRS (*Green Building Rating Systems*). The results indicate that all GBRS evaluated the deep bioclimatic house in warm climates as more sustainable than the conventional counterpart. Nevertheless, the scores exhibited considerable variability among the rating systems. Only three GBRS clearly identified the significant advantages associated with deep bioclimatic design, whereas the remaining systems assigned relatively low scores, and three of them scarcely reflected its benefits. This occurred despite the fact that the analyzed bioclimatic house demonstrated a 56.0% reduction in energy consumption compared to a conventional building, in addition to other environmental benefits. Based on the average results across the 11 GBRS, the contribution of deep bioclimatic design to building sustainability was estimated at 11.99%. However, when considering only the average results of the three GBRS that most effectively captured bioclimatic performance, this contribution increased to 21.08%. These findings are consistent with previous research and may therefore be extrapolated to residential or non-residential buildings incorporating deep bioclimatic design principles in warm climates, which enable thermal regulation and the maintenance of indoor thermal comfort without reliance on air-conditioning systems.

Key words: Deep bioclimatic design, Green Building Rating System, improving future GBRS, passive design, sustainable evaluation.

1. Introduction

Building sustainability has become a central objective in contemporary architectural and environmental research. Within this context, this study quantifies the contribution of deep bioclimatic design to the sustainability level of a building in warm climates. In this study, warm climates are defined as regions characterized by persistently high temperatures, requiring year-round cooling.

Deep bioclimatic design is defined as the development of buildings capable of achieving thermal self-regulation without the use of energy-consuming devices [1-3]. Buildings designed under this approach are characterized by a specific orientation and architectural configuration that enable the maintenance of indoor thermal comfort throughout the year. In winter, thermal comfort is achieved through optimized orientation, the greenhouse effect, and a set of integrated passive architectural strategies. In summer, cooling is provided through appropriate orientation, solar protection systems, and the cooling of night air through specially designed underground galleries.

The advantages of deep bioclimatic design have been extensively analyzed in previous studies [1-9], which report substantial reductions in energy consumption, emissions, and waste, as well as improvements in occupants' quality of life and a reduction in illness prevalence. However, most existing research has

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focused on individual performance indicators, primarily energy consumption [1, 5, 8, 10-12], thereby limiting a comprehensive understanding of the broader sustainability implications of this design approach.

Consequently, relatively few studies have evaluated the contribution of deep bioclimatic design to the overall sustainability level of buildings using integrated assessment frameworks [13-16]. And there are no studies that have comprehensively evaluated the contribution of deep bioclimatic design in warm climates.

To holistically assess and quantify the sustainability of buildings, multivariate assessment tools known as *Green Building Rating Systems* (GBRS) have been developed [17-21], and are now widely applied in both research and practice. Accordingly, the present study employs the 11 most internationally representative GBRS to comprehensively evaluate the contribution of bioclimatic design to overall building sustainability.

For this purpose, a house incorporating deep bioclimatic design principles—the *Mariposa* house (Fig. 1)—was selected and compared with a conventionally designed house. The *Mariposa* house features a deep bioclimatic design that ensures indoor thermal comfort throughout the year without the use of heating or air-conditioning systems. In addition, it does not require mechanical ventilation systems or artificial lighting during daytime hours. Considering that this dwelling achieves an energy saving of 70.3% compared to a conventional house, together with additional environmental benefits (absence of emissions), economic advantages (reduced costs, lower maintenance requirements, and fewer system failures), and benefits for human health (reduced noise, emissions, vibrations, and odors), it would be reasonable to expect that current GBRS adequately capture these attributes and assign correspondingly high sustainability scores.

2. Description of the Houses Studied: *Mariposa-Bio* and *Mariposa-No-Bio*

To accurately determine the contribution of the *deep bioclimatic design* in the sustainable score of a building, a deep bioclimatic house (*Mariposa* house, called *Mariposa-bio* in this work) was compared with a reference baseline, its hypothetical non bioclimatic version, conventionally designed *(Mariposa-no-bio*). In both cases the evaluation was carried out using 11 of the best, and internationally well known, GBRS. To simplify the study, only the indicators with different scores for the two cases are shown in the comparison to obtain scores that depend exclusively on the *deep bioclimatic design*.

Fig. 1 ***Mariposa house*. Cali. Colombia (Projected by Luis de Garrido). North façade.**

2.1 Description of the House with Deep Bioclimatic Design. Mariposa-Bio

2.1.1 General Information

Mariposa house is located in Cali (Colombia), and has an area 407.62 m^2 and a useful area of 287.3 m^2 on two floors and a basement (Figs. 1, 2, 3, 4) [22]. The ground floor has a central double-height patio, a living room, two kitchens, a pantry, three bathrooms, a bedroom and a studio (Fig. 5). The first floor has two bedrooms and two bathrooms (Fig. 6). *Mariposa-bio* was built in 2014 and thanks to its *deep bioclimatic design* is capable of maintaining a comfortable interior temperature, so that its energy consumption is 70.3% less than that of a conventional house of the same surface area and characteristics. It also does not need lighting during the day nor ventilation devices. Due to its low energy consumption, *Mariposa* house is self-sufficient in energy and water at a very low price [22].

Fig. 2 ***Mariposa house*. Cali. Colombia (Projected by Luis de Garrido). South façade.**

Fig. 3 ***Mariposa house*. Cali. Colombia (Projected by Luis de Garrido).**

Fig. 4 The *Mariposa house* has two types of roofs. The green roof covers the ground and first floor spaces, while the central double-height space has a sloping roof. The special design of the sloping roof forces the heated air to rise and escape through the highest part of the north-facing windows. This extraction of hot air creates a suction current which, in turn, creates a current of cool air by extracting the cooled air in the basement.

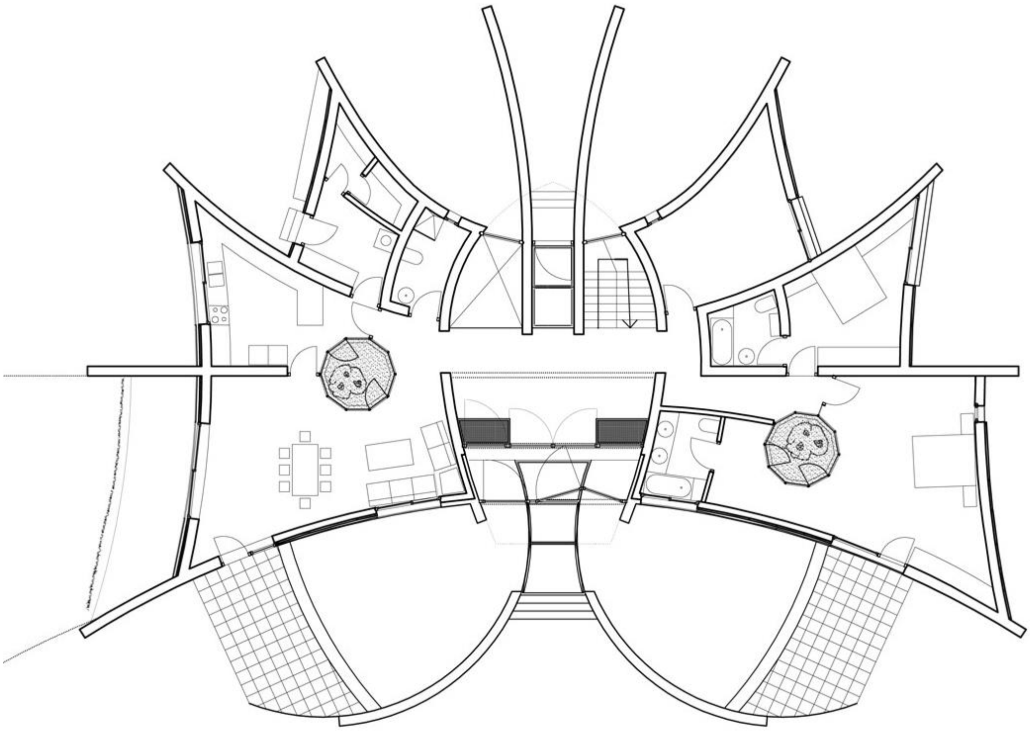

Fig. 5 *Mariposa* house. Ground floor layout.

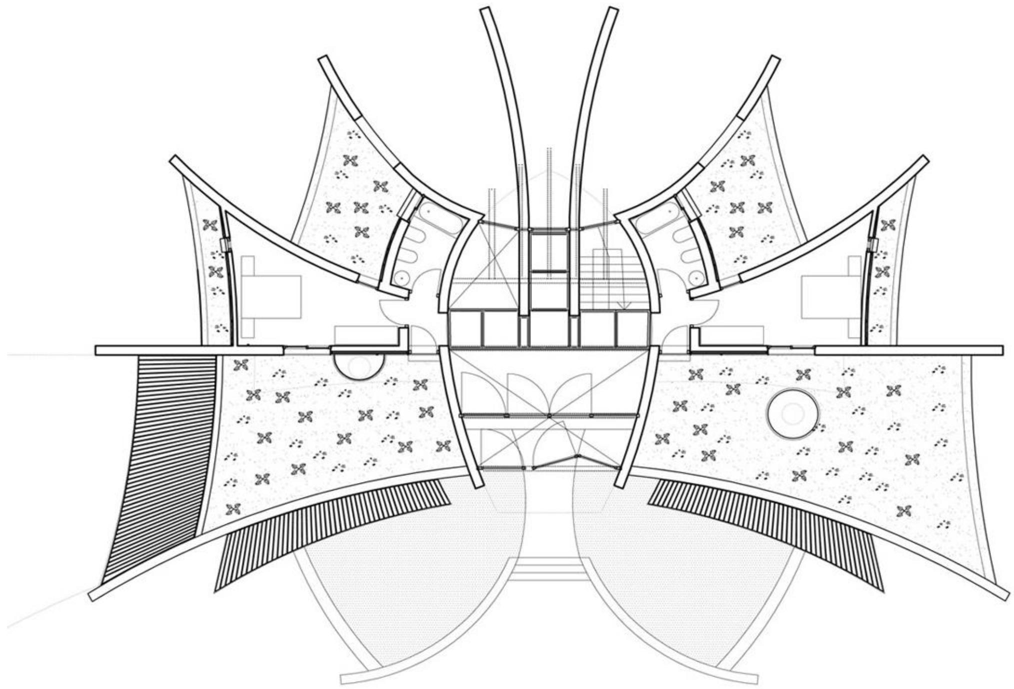

Fig. 6 ***Mariposa*** **house. First floor layout.**

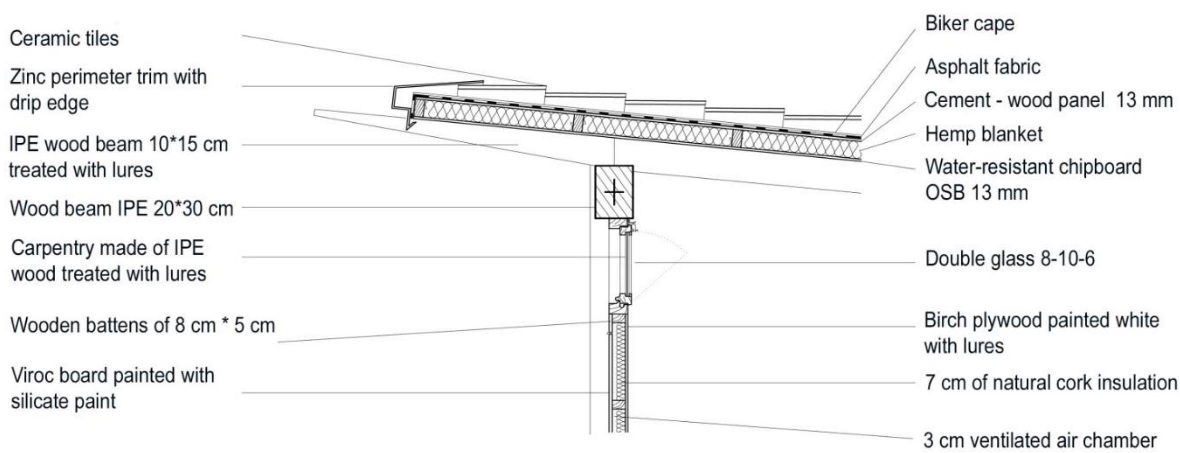

Fig. 7 **Construction detail of the sloping roof of** ***Mariposa house.***

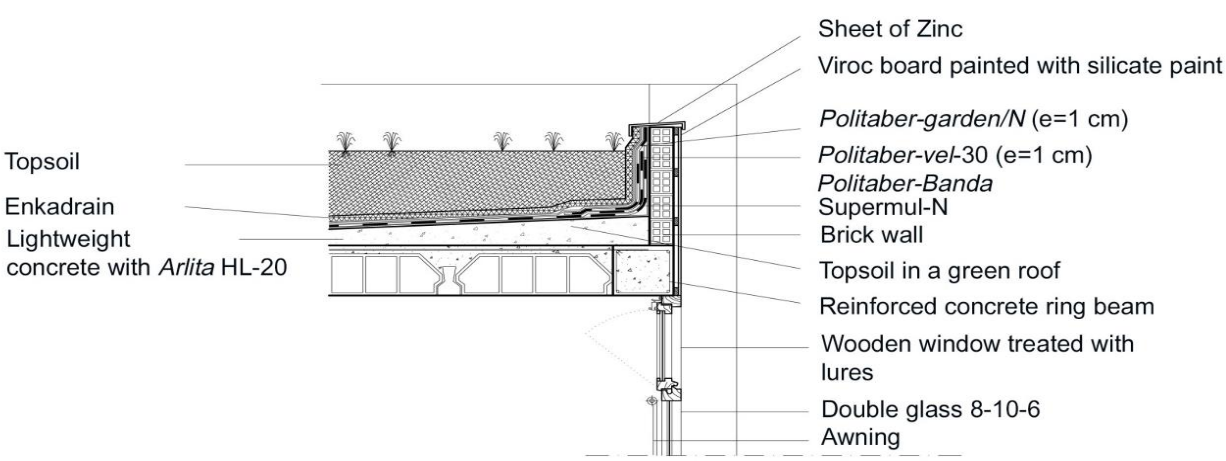

Fig. 8 **Construction detail of the green roof of** ***Mariposa house.***

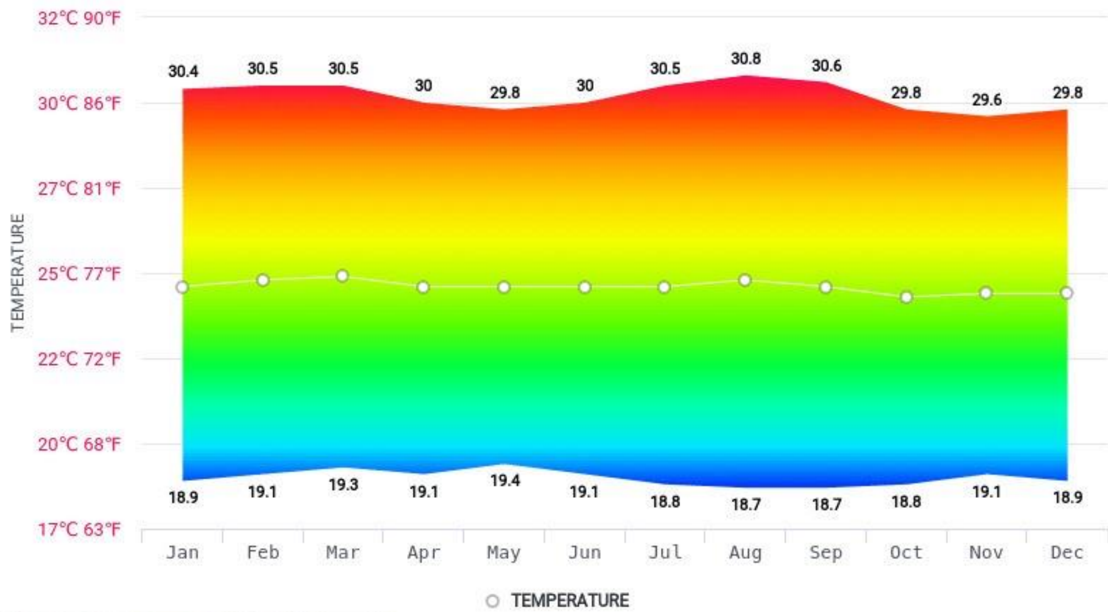

Fig. 9 Average day and night temperatures 1961-2017, in Cali, Colombia [23].

The house's design incorporates vertical and horizontal solar shading to regulate the access of solar radiation to the interior of the house as needed throughout the year.

2.1.2 Deep Bioclimatic Design

In this study, *deep bioclimatic design* is defined as creating buildings capable of thermal self-regulation, providing a comfortable interior temperature, without the need for heating and air conditioning equipment. Achieving this requires good professional skills, although in extreme climates, occasional heating may still be needed.

In Cali, daytime temperatures hover around 31 °C [23] (Fig. 9), and in warm climates, a comfort temperature of around 24 °C is considered, so the house must be able to reduce the outside temperature by about 7 °C. To achieve this, the following design strategies have been used (Figs. 10, 11):

- North-south orientation;
- High thermal inertia on the internal side of the enclosure;
- Adequate insulation on the external side of the enclosure;
- Cold generation in underground galleries;
- Cold generation through optimized internal night ventilation;
- Solar protections allow minimum solar radiation to enter the building in summer;
- Served spaces to the south, serving spaces to the north.

Firstly, the house cools down in summer, avoiding heating up during the day, due to its orientation, the arrangement of glass and the special solar protections. Secondly, the house is designed so that the cold night air is further cooled in the underground galleries, penetrates the interior of the house, and cools it during the night, while the house remains cool during the day due to solar protections, high interior thermal inertia and its exterior insulation. A maximum internal temperature of about 19 ºC is maintained in summer during the night and 24 ºC during daylight. The covered interior courtyard plays an important role in continuously cooling the house (Figs. 10, 11, 12, 13).

2.1.3 House Energy Consumption

Due to the *bioclimatic design*, the house does not need heating devices, air conditioning, or mechanical ventilation, and as the owners are highly conscious of reducing energy consumption as much as possible, the house has very few appliances, with a total power of 8,815 W (Table 1) with an annual consumption of 27.31 kWh/m^2 (Table 2).

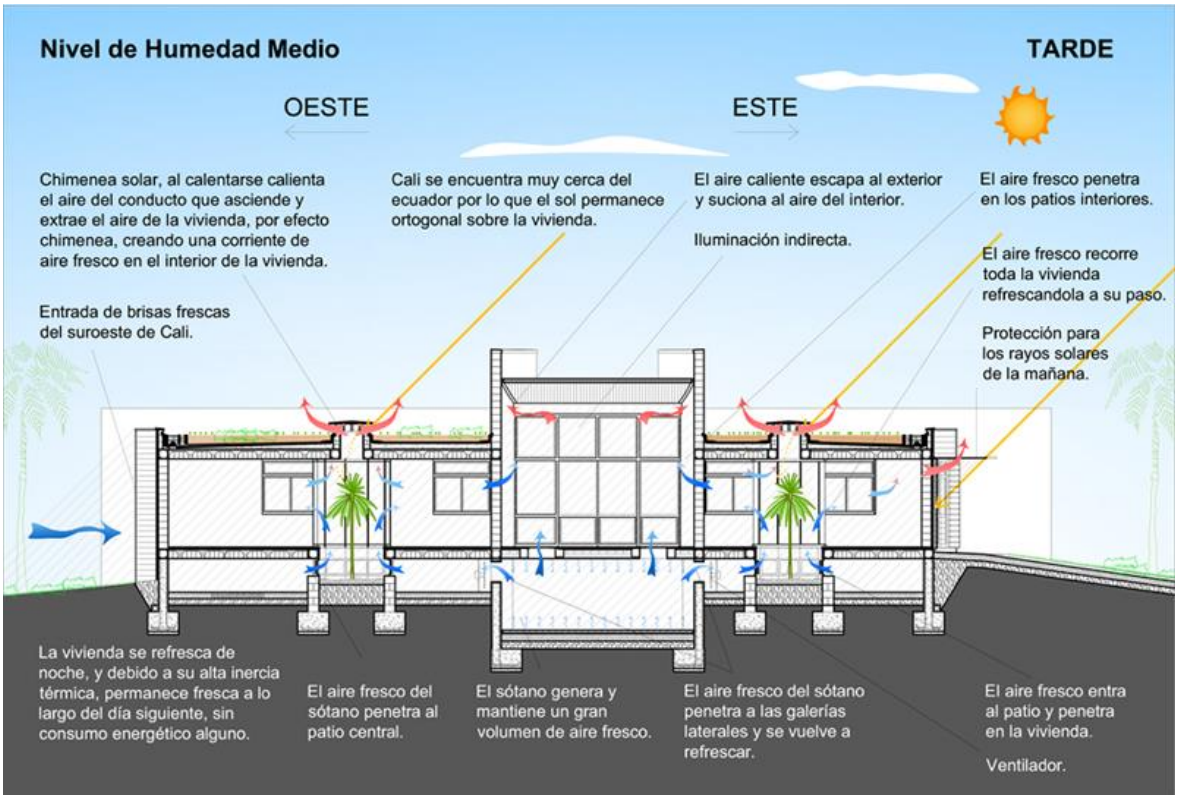

Fig. 10 ***Mariposa*** **house. Bioclimatic strategies to cool the house (afternoon).**

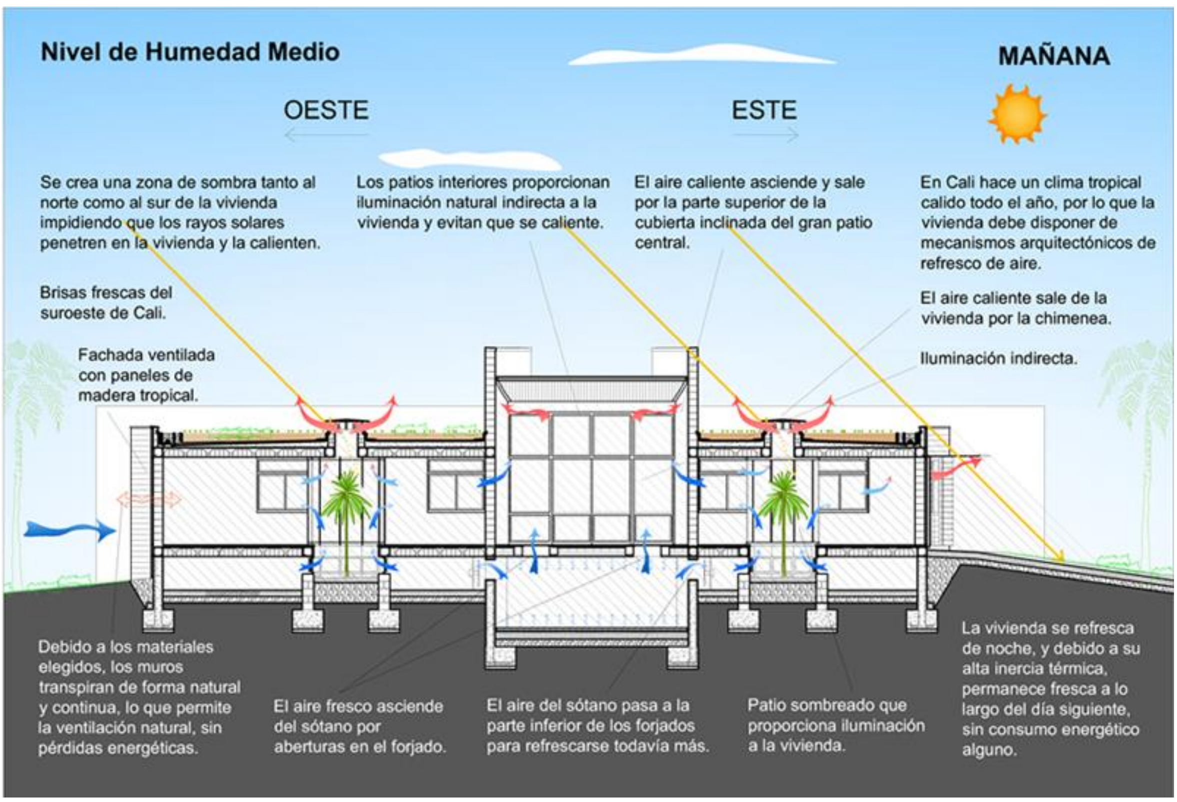

Fig. 11 ***Mariposa*** **house. Bioclimatic strategies to cool the house (morning).**

Fig. 12 Interior of *Mariposa* house. Covered central courtyard.

Fig. 13 Glass floors allow for greater lighting inside the house.

Table 1 Total power of the appliances in *Mariposa-bio*.

Fridge (2)	300 W (average power)
Induction hob (2)	1,300 W
Microwave (2)	1.200 W
Washing machine (2)	2,000 W
TVs	450 W
PCs	200 W
Lighting	385 W
Garden lighting	280 W
Water purification	1,400 W
Total power	8,815 W

Table 2 Total energy consumption per m^2 of *Mariposa-bio*.

287.3 m^2	Power W (watts)	Active time (hours)	Energy per year (kWh/year)	Energy year/m^2 (kWh/m^2/year)
Fridges (average power)	300	24 h. * 365	2,628	9.14
Induction hobs	1,300	2 h. * 365	949	3.30
Microwaves	1,200	1 h. * 365	438	1.52
Washing machines	2,000	1 h. * 365	730	2.54
TVs	450	3 h. * 365	492	1.71
PCs	200	8 h. * 365	584	2.03
Lighting	385	8 h. * 365	1,124	3.91
Garden lighting	280	4 h. * 365	408	1.42
Water purification	1,400	1 h. * 365	511	1.77

Total energy consumed per m^2: 27.31 kWh/m^2/year.

2.1.4 Energy Self-sufficiency

To achieve energy self-sufficiency at an affordable cost, a three-phase strategy has been followed:

1. Informing the owners to use as few devices as possible.

2. Carrying out an optimal *bioclimatic design*

3. Correctly managing the devices incorporated into the house.

Due to its specialized *bioclimatic design*, the house does not need heating or air conditioning. It is estimated that the maximum total power of all the devices that can be activated at the same time is 3,500 watts, with occasional peak requirements of up to 4,000 watts. To meet these needs, a photovoltaic system with ten photovoltaic solar collectors has been installed. This system generates approximately 5,000 watts at peak output, so that the batteries can provide a power of at least 4,000 W (as usual, batteries cannot supply their full power, but rather around 80%). The photovoltaic system necessary costs €8,500 including VAT.

2.2 Description of the Non-bioclimatic Design. Mariposa-No-Bio

2.2.1 Description and Disadvantages

A conventionally designed house in Cali requires air conditioning throughout the year to maintain a comfortable interior temperature and artificial lighting in some of its rooms, even during the day. As a result, the house has an additional cost (price of the equipment and price of the space to house them), requires more maintenance, generates harmful emissions, and reduces the well-being and health of its occupants (noise, odors, vibrations).

2.2.2 House Energy Consumption

The total constructed area of *Mariposa-no-bio* is 287.3 m^2. In Cali, the average power of air conditioning systems is, at least, 90 W/m^2 [24]. Therefore, the *Mariposa-no-bio* house should incorporate an air conditioning system with a minimum power of 25,857 W (287.3 m^2 * 90 W/m^2 = 25,857 W). Assuming a COP of 4, the power of the air conditioning units could be only 6,914 W. This way, the total power of the *Mariposa-no-bio* electromechanical devices would be at least 15,729 W (6,914 W + 8.815 W) (Table 1), and its energy consumption (per m^2) would be 61.96 kWh/m^2/year (Table 3).

Mariposa-bio consumes only 44.0% of what *Mariposa-no-bio* would consume (27.31 kWh/m^2/year/ 61.96 kWh/m^2/year), from which it follows that a good *bioclimatic architectural design* is capable of generating a minimum energy saving of 56.0%, in warm climates, where heating is not usually needed, but air conditioning equipment is required.

2.2.3 Energy Self-sufficiency

The total power of the *Mariposa-no-bio* devices is 15,729 W, and, although not all devices have to be connected at the same time, the minimum power of the photovoltaic panels that should be installed to generate electrical energy for the house would be around 12,000 W. The photovoltaic system costs about €25,000 including VAT. That is, for *Mariposa-no-bio* to be self-sufficient in energy, three times as many photovoltaic panels would have to be installed than for *Mariposa-bio*, and at an economic cost three times greater.

It is thus essential to carry out an optimal *bioclimatic design* to achieve energy self-sufficiency at an affordable cost.

3. Comparative Evaluation of *Mariposa-Bio* and *Mariposa-No-Bio*

The evaluation of *Mariposa-bio*, and *Mariposa-no-bio* was carried out using a selection of the most important and representative existing GBRS (*Green Building Rating Systems*).

3.1 Choice of the Most Emblematic GBRS

Five criteria were applied to select the principal *Green Building Rating Systems* (GBRS) for the sustainability assessment. These criteria included: (i) geographical and territorial representation; (ii) the number of buildings evaluated by each system; (iii) the number of citations indexed in the *Scimago* database; (iv) the number of citations recorded in Google Scholar; and (v) the availability of comprehensive technical manuals and user guides.

Based on these criteria, a comprehensive inventory of GBRS was compiled [25], from which the most relevant systems were identified. It should be noted that only rating systems with publicly available and fully operational manuals were considered eligible for inclusion. As a result, a total of 11 GBRS were selected, which constitutes a sufficiently large and representative sample for the purposes of this study: ASGB (Assessment Standard for Green Building) [26], BEAM (Building Environmental Assessment Method) [27], BREEAM (Building Research Establishment Environmental Assessment Methodology) [28, 29], CEDES [30, 31], DNGB (Deutsche Gesellschaft für Nachhaltiges Bauen) [32], GBI (Green Building Index) [33], GG (Green Globes) [34], GS (Green Star) [35], IGBC (Indian Green Building Council) [36], LEED (Leadership in Energy and Environmental Design) [37] and SBTools [38].

Table 3 Total energy consumption per m^2 of *Mariposa-no-bio*.

287.3 m^2	Power W (watts)	Active time (hours)	Energy year (kWh-year)	Energy year/m^2 (kWh/m^2/year)
Fridges (average power)	300	24 h. * 365	2,628	9.14
Induction hobs	1,300	2 h. * 365	949	3.30
Microwaves	1,200	1 h. * 365	438	1.52
Washing machines	2,000	1 h. * 365	730	2.54
TVs	450	3 h. * 365	492	1.71
PCs	200	8 h. * 365	584	2.03
Lighting	385	8 h. * 365	1,124	3.91
Garden lighting	280	4 h. * 365	408	1.42
Water purification	1,400	1 h. * 365	511	1.77
Cooling	6,914	8 h. * 180	9,956	34.65

Total energy consumed per m^2: 61.96 kWh/m^2/year.

3.2 Comparative Evaluation Results of Mariposa-Bio, and Mariposa-No-Bio

To evaluate the contribution of the *bioclimatic design* to the general level of sustainability, an evaluation of *Mariposa-bio* with respect to *Mariposa-no-bio* was carried out using the chosen GBRS. As it is a comparative evaluation, only the indicators whose score is different in each case were taken into account. We will call the set of indicators whose score varies when comparing a bioclimatic building with another that is not a "bio-group".

The evaluation tables first show for both designs:

- The score given to each indicator.
- The maximum possible score for each indicator.
- The weight of the indicator within the category to which it belongs.
- The weight of the category.
- The conversion factor of the scoring scale of each method, to a scale of 0-100 (since some GBRS score from 0 to 75, others from 0 to 100, others from 0 to 110, others from 0 to 1,000. The conversion factors used are therefore: 100/75, 100/100, 100/110, 100/1,000).

By multiplying the percentage score of an indicator (score/maximum score) by its weight within the category, by the weight of the category, and by the conversion coefficient, yields a value (from 0 to 100), which represents the contribution of each indicator in the total score. Summing the score of all the indicators of the "bio-group" gives the total score of each group to both *Mariposa-bio* and *Mariposa-no-bio*. Subtracting the two scores yields the contribution of the *bioclimatic design* is obtained in the final score provided by each GBRS.

It should be noted that not all systems have a similar structure, so that the structure of the different tables is not the same. But essentially all the tables show the same: the final score of each indicator on a scale from 0 to 100, and the total score.

To describe the evaluation process and the contribution of each indicator in the final evaluation of the building, let us take an example from ASGB (Table 4).

The ASGB indicator "O.D.F.N.V. (optimized design for natural ventilation)" has a maximum score of 8 points. This indicator has a weight of 8/100 within the "H.C. (health and comfort)" category, and in turn this category has a weight of 10 out of 110 (ASGB has a total evaluation range of 0 to 110).

- In the case of *Mariposa-bio*, the maximum score (8) was given to the O.D.F.N.V. indicator, so that the percentage score is ((8 / 8) = 1). By multiplying this value (1) by the weight of the O.D.F.N.V indicator in the H.C. category, a value of ((1) * (8 / 100)) is obtained, i.e. 0.08. Multiplying this value by the weight of the H.C. category in the total score gives (0.08 * (10 / 100)) = 0.008, based on a score of (0-110). Converting this percentage to a common base of (0-100), the final score is (0.008 * (100 / 110)) = 0.0073, i.e. 0.73%.
- In the case of *Mariposa-no-bio*, it was given a score of 1 out of a maximum of 8, so the percentage score is, ((1 / 8) = 0.125). Multiplying this value (0.125) by the weight of the O.D.F.N.V indicator in the H.C. category gives a value of (0.125 * (8 / 100)), that is, 0.01. Multiplying this value by the weight of the H.C. category in the total score gives (0.01 * (10 / 100)) = 0.001, percentage based on a score of (0-110). Converting this percentage to a common base of (0-100), the final score is (0.001 * (100 / 110)) = 0.0009, i.e. 0.09%.

Repeating the process for the 5 indicators for the "bioclimatic design" of a building in ASGB (Table 4), *Mariposa-bio* has a score of 5.74%, compared to 3.72% for *Mariposa-no-bio*, i.e. according to ASGB, a bioclimatic house like *Mariposa-no-bio* has a higher sustainability level of 2% (5.74-3.72) than a conventional building (Table 4).

3.2.1 ASGB Evaluation

ASGB contains 5 *bioclimatic design* indicators, each of which gave different scores when evaluating *Mariposa-bio*, and *Mariposa-no-bio*. This difference in both cases was only 2% because ASGB does not consider many important aspects of *bioclimatic design* (such as: bioclimatic architectural design, solar energy, waste and emissions generated in maintenance and increased health and quality of life).

3.2.2 BEAM Evaluation

BEAM contains 6 *bioclimatic design* indicators, each of which gave different scores when evaluating *Mariposa-bio*, and *Mariposa-no-bio*. This difference in both cases was only 12.17% because BEAM does not consider many important aspects of *bioclimatic design* (such as: bioclimatic architectural design and solar energy).

3.2.3 BREEAM Evaluation

BREEAM contains 4 *bioclimatic design* indicators, each of which gave different scores when evaluating *Mariposa-bio*, and *Mariposa-no-bio*. This difference in both cases was only 10.24% because BREEAM does not consider many important aspects of *bioclimatic design* (such as: bioclimatic architectural design, waste and emissions generated in maintenance and increased health and quality of life).

Table 4 ASGB indicators involved in bioclimatic design. Score differences between *Mariposa-bio* and *Mariposa-no-bio*.

Involved indicators		*Mariposa-bio*						*Mariposa-no-bio*					
Indicators	Category	Score	Max. score	Indicator weight (*9)	Category weight	Result (0-110)	Result (0-100)	Score	Max. score	Indicator weight	Category weight	Result (0-110)	Result (0-100)
O.D.F.N.V.(*1)	H.C.(*6)	8	8	8/100	10%	0.80	0.73	1	8	8/100	10%	0.10	0.09
U.O.D.T.R.S.I.(*2)	H.C.(*6)	9	9	9/100	10%	0.90	0. 82	1	9	9/100	10%	0.90	0.82
T.E.P.O.(*3)	R.C.(*7)	15	15	15/200	20%	1.50	1.36	12	15	15/200	20%	1.20	1.09
M.R.B.E.C.(*4)	R.C.(*7)	10	10	10/200	20%	1.00	0.91	6	10	10/200	20%	0.60	0.55
M.F.R.H.S.C.(*5)	I.I.(*8)	40	40	40/190	10%	2.11	1.92	25	40	40/190	10%	1.32	1.20
Partial score					5.74%						3.74%		
Difference		2.00%											

*1 Optimized design for natural ventilation, *2 Use of devices to regulate shade inside, *3 Thermal envelope performance optimization, *4 Measures to reduce building energy consumption, *5 Measures to further reduce heating system consumption, *6 Health and comfort, *7 Resource conservation, *8 Improvement and innovation, *9 This system does not assign a weight to the indicator, but is determined by the maximum score of the indicator divided by the maximum score of the category.

Table 5 BEAM indicators involved in bioclimatic design. Score differences between *Mariposa-bio* and *Mariposa-no-bio.*

Involved indicators		*Mariposa-bio*						*Mariposa-no-bio*					
Indicators	Category	Score	Max. score	Indicator weight (*10)	Category weight	Result (0-110)	Result (0-100)	Score	Max. score	Indicator weight	Category weight	Result (0-110)	Result (0-100)
D.C.C.A.(*1)	S.S.(*7)	2	2	2/39	15%	0.77	0.70	1	2	2/39	15%	0.38	0.35
L.C.P.D.(*2)	E.U.(*8)	6	6	6/44	29%	3.94	3.59	2	6	6/44	29%	1.31	1.20
R.CO^2.E.(*3)	E.U.(*8)	15	15	15/44	29%	9.89	8.99	7	15	15/44	29%	4.61	4.20
P.E.D.(*4)	E.U.(*8)	3	3	3/44	29%	1.91	1.79	1	3	3/44	29%	0.66	0.60
E.V.(*5)	H.W (*9)	4	4	4/29	22%	3.04	2.76	0	4	4/29	22%	0.00	0.00
I.V.(*6)	H.W (*9)	1	1	1/29	22%	0.75	0.68	0	1	1/29	22%	0.00	0.00
Partial score					18.50%						6.34%		
Difference		12.17%											

*1 Design for climate change adaptation, *2 Low carbon passive design, *3 Reduction of CO^2 emissions, *4 Peak electricity demand, *5 Enhanced ventilation, *6 Indoor vibration; *7 Sustainable site, *8 Energy use, *9 Health and wellbeing, *10 This system does not assign a weight to the indicator but is determined by the maximum score of the indicator divided by the maximum score of the category.

Table 6 BREEAM indicators involved in bioclimatic design. Score differences between *Mariposa-bio* and *Mariposa-no-bio.*

Involved indicators		*Mariposa-bio*						*Mariposa-no-bio*					
Indicators	Category	Score	Max. score	Indicator weight	Category weight	Result (0-110) (*5)	Result (0-100)	Score	Max. score	Indicator weight	Category weight	Result (0-110)	Result (0-100)
ENE01 (*1)	ENE	13	31	41.93%	16%	6.71	6.10	0	31	0%	16%	0	0
ENE 04 (*2)	ENE	13	31	41.93%	16%	6.71	6.10	1	31	3.23%	16%	0.52	0.47
ENE 05 (*3)	ENE	13	31	41.93%	16%	6.71	6.10	1	31	3.23%	16%	0.52	0.47
INN (*4)	INN	5	10	50%	10%	5	4.55	2	10	0.20%	10%	2.00	1.82
Partial score							22.85%						2.76%
Difference		20.09%											

Table 7 CEDES indicators involved in bioclimatic design. Score differences between *Mariposa-bio* and *Mariposa-no-bio*.

Involved indicators		*Mariposa-bio*						*Mariposa-no-bio*					
Indicators	Category	Score	Max. score	Indicator weight	Category weight	Result	Result (0-100)	Score	Max. score	Indicator weight	Category weight	Result	Result (0-100)
2.6	BD (*1)	5	5	45,8%	36%	0.1648	16.48	1	5	45,8%	36%	0.0329	3.29
3.1	SE (*2)	5	5	60%	13%	0.078	7.8	2	5	60%	13%	0.0156	1.56
4.5	WEM (*3)	5	5	20%	12%	0.0192	1.92	2	5	20%	12%	0.0048	0.48
5	HE (*4)	5	5	100%	8%	0.064	6.4	2	5	100%	8%	0.032	3.2
Partial score							32.6%						8.53%
Difference		24.07%											

*1 BD: Bioclimatic Architectural Design, *2 SE: Solar Energy, *3 WEM: Waste and emissions generated in building maintenance, *4 HE: Increased health and quality of life of building residents.

3.2.4 Evaluation Using CEDES

CEDES contains 4 *bioclimatic design* indicators, each of which gave different scores when evaluating *Mariposa-bio*, and *Mariposa-no-bio*. This difference in both cases was 24.07 % because CEDES is very complete and considers all the possible aspects and advantages of *bioclimatic design*.

3.2.5 DNGB Evaluation

DNGB contains 7 *bioclimatic design* indicators, each of which gave different scores when evaluating *Mariposa-bio*, and *Mariposa-no-bio*. The score difference for both cases is very high, 17.69 % despite the fact that DNGB does not take into account many basic aspects of *bioclimatic design* (such as: bioclimatic architectural design, waste and emissions generated in maintenance and increased health and quality of life).

3.2.6 GBI Evaluation

GBI contains 3 *bioclimatic design* indicators, each of which gave different scores when evaluating *Mariposa-bio*, and *Mariposa-no-bio*. This difference in both cases was only 4% because GBI does not consider many important aspects of *bioclimatic design* (such as: bioclimatic architectural design, solar energy, and waste and emissions generated in maintenance).

3.2.7 GG Evaluation

GG contains 2 *bioclimatic design* indicators, each of which gave different scores when evaluating *Mariposa-bio*, and *Mariposa-no-bio*. This difference in both cases was only 10.50 % because GG does not consider many important aspects of *bioclimatic design* (such as: bioclimatic architectural design, solar energy, waste and emissions generated in maintenance and increased health and quality of life).

3.2.8 GS Evaluation

GS contains 10 *bioclimatic design* indicators, each of which gave different scores when evaluating *Mariposa-bio*, and *Mariposa-no-bio*. The score difference for both cases is very high, 19.09 %, despite the fact that GS does not take into account some basic aspects of *bioclimatic design* (such as: bioclimatic architectural design and increased health and quality of life).

3.2.9 IGBC Evaluation

IGBC contains 2 *bioclimatic design* indicators, each of which gave different scores when evaluating *Mariposa-bio*, and *Mariposa-no-bio*. This difference in both cases was only 9.33 % because IGBC does not consider many important aspects of *bioclimatic design* (such as: bioclimatic architectural design, solar energy, waste and emissions generated in maintenance).

Table 8 DNGB indicators involved in bioclimatic design. Score differences between *Mariposa-bio* and *Mariposa-no-bio*.

Involved indicators		*Mariposa-bio*						*Mariposa-no-bio*					
Indicators	Category (*1)	Score	Max. score	Indicator weight (*2)	Category weight	Result	Result (0-100)	Score	Max. score	Indicator weight	Category weight	Result	Result (0-100)
ENV 1.1	ENV	122.5	130	10/24	25%	-	9.82	60	130	10/24	25%	-	4.81
ENV 1.2	ENV	110	135	5/24	25%	-	4.24	65	135	5/24	25%	-	2.51
ECO 1.1	ECO	110	130	4/10	25%	-	8.46	47,50	130	4/10	25%	-	3.65
ECO 2.6	ECO	100	110	2/10	25%	-	4.55	70	110	2/10	25%	-	3.18
SOC 1.1	SOC	85	105	2/10	25%	-	4.05	45	105	2/10	25%	-	2.14
SOC 1.2	SOC	105	110	2/10	25%	-	4.77	75	110	2/10	25%	-	3.41
SOC 1.4	SOC	100	100	2/10	25%	-	5.00	70	100	2/10	25%	-	3.50
Partial score							40.89%						23.20%
Difference		17.69%											

*1 Category is named as Topic on Criteria set of DNGB, *2 This system does not assign a weight to the indicator, but is determined by the maximum score of the indicator divided by the maximum score of the category.

Table 9 GBI indicators involved in bioclimatic design. Score differences between *Mariposa-bio* and *Mariposa-no-bio.*

Involved indicators		*Mariposa-bio*						*Mariposa-no-bio*					
Indicators	Category	Score	Max. score	Indicator weight	Category weight	Result	Result (0-100)	Score	Max. score	Indicator weight	Category weight	Result	Result (0-100)
EE3	EE (*1)	5	5	-	-	-	5	3	5	-	-	-	3
EQ1	IEQ (*2)	2	2	-	-	-	2	1	2	-	-	-	1
IN1 (*4)	INN (*3)	1	1	-	-	-	1	0	1	-	-	-	0
Partial score							8%						4%
Difference		4%											

*1 Energy efficiency, *2 Indoor environment quality, *3 Innovation, *4 External shading devices.

Table 10 GG indicators involved in bioclimatic design. Score differences between *Mariposa-bio* and *Mariposa-no-bio.*

Involved indicators		*Mariposa-bio*						*Mariposa-no-bio*					
Indicators	Category	Score	Max. score	Indicator weight	Category weight	Result (0-1000)	Result (0-100)	Score	Max. score	Indicator weight	Category weight	Result (0-1000)	Result (0-100)
3.1 EP (*1)	ENERGY	180	180	-	-	180	18	90	260	-	-	90	9
3.4 RSE (*2)	ENERGY	30	30	-	-	30	3	15	260	-	-	15	1.5
Partial score							21%						10.5%
Difference		10.5%											

*1 Energy Performance, *2 Renewable Sources of Energy.

Table 11 GS indicators involved in bioclimatic design. Score differences between *Mariposa-bio* and *Mariposa-no-bio.*

Involved indicators		*Mariposa-bio*						*Mariposa-no-bio*					
Indicators	Category	Score	Max. score	Indicator weight	Category weight	Result (0-110)	Result (0-100)	Score	Max. score	Indicator weight	Category weight	Result (0-110)	Result (0-100)
5	MGMt (*1)	2	2	-	-	2	1.82	1	2	-	-	1	0.91
9	IEQ (*2)	4	4	-	-	4	3.64	2	4	-	-	2	1.82
10	IEQ	3	3	-	-	3	2.73	1	3	-	-	1	0.91

Table 11 to be continued

13	IEQ	2	2	-	-	2	1.82	1	2	-	-	1	0.91
14	IEQ	2	2	-	-	2	1.82	1	2	-	-	1	0.91
15	ENE (*3)	20	20	-	-	20	18.18	10	20	-	-	10	9.09
16	ENE	2	2	-	-	2	1.82	1	2	-	-	1	0.91
25	LU (*4)	1	1	-	-	1	0.91	0	1	-	-	0	0.00
28	EMI (*5)	1	1	-	-	1	0.91	0	1	-	-	0	0.00
29	EMI	1	1	-	-	1	0.91	0	1	-	-	0	0.00
Partial score							34.55%						15.45%
Difference		19.09%											

*1 Management, *2 Indoor environment quality, *3 Energy, *4 Land use, *5 Emissions, *6 Green star scores up to 100 points and adds 10 for innovation.

Table 12 Indicators of IGBC involved in bioclimatic design. Score differences between *Mariposa-bio* and *Mariposa-no-bio*.

Involved indicators		*Mariposa-bio*						*Mariposa-no-bio*					
Indicators	Category	Score	Max. score	Indicator weight	Category weight	Result (0-110)	Result (0-100)	Score	Max. score	Indicator weight	Category weight	Result (0-110)	Result (0-100)
EE C1	EE	7	10	-	-	7	9.33	6	10	-	-	6	8
IEQ C6	IEQ	4	4	-	-	4	5.33	2	4	-	-	2	2.67
Partial score							20%						10.67%
Difference		9.33%											

Table 13 LEED indicators involved in bioclimatic design. Score differences between *Mariposa-bio* and *Mariposa-no-bio.*

Involved indicators		*Mariposa-bio*						*Mariposa-no-bio*					
Indicators	Category	Score	Max. score	Indicator weight	Category weight	Result (0-110)	Result (0-100)	Score	Max. score	Indicator weight	Category weight	Result (0-110)	Result (0-100)
AEU (*1)	EA (*2)	36	36	-	-	36	32.72	27	36	-	-	27	24.54
Partial Score							32.72%						24.54%
Difference		8.18%											

Indicators of the manual for single-family housing. *1 EAC Annual Energy Use, *2 Energy and Atmosphere.

3.2.10 LEED Evaluation

LEED is the most limited GBRS when assessing bioclimatic design since it contains only 1 *bioclimatic design* indicator, which gave different scores when evaluating *Mariposa-bio*, and *Mariposa-no-bio*. This difference in both cases was only 8.18 % because LEED does not consider many important aspects of *bioclimatic design* (such as: bioclimatic architectural design, solar energy, waste and emissions generated in maintenance and increased health and quality of life).

3.2.11 SBTools Evaluation

SBTools contains 18 *bioclimatic design* indicators, each of which gave different scores when evaluating *Mariposa-bio*, and *Mariposa-no-bio*. This difference in both cases was only 4.83 % because SBTools does not consider many important aspects of *bioclimatic design* (such as: bioclimatic architectural design, solar energy, waste and emissions generated in maintenance).

Table 14 SBTools indicators involved in bioclimatic design. Score differences between *Mariposa-bio* and *Mariposa-no-bio.*

Involved indicators		*Mariposa-bio*						*Mariposa-no-bio*					
Indicators	Category	Score	Max. score	Indicator weight (*9)	Category weight	Result	Result (0-100)	Score	Max. score	Indicator weight	Category weight	Result	Result (0-100)
A 2.3	USIS (*1)	5	5	1.62%	-	-	1.62	0	5	1.62%	-	-	0
A 2.5	USIS	5	5	0.81%	-	-	0.81	0	5	0.81%	-	-	0
A 2.6	USIS	5	5	0.20%	-	-	0.20	0	5	0.20%	-	-	0

Table 14 to be continued

B 2	ERC (*2)	5	5	1.60%	-	-	1.60	0	5	1.60%	-	-	0
D 1.6	IEQ (*3)	5	5	0.20%	-	-	0.20	0	5	0.20%	-	-	0
D 1.7	IEQ	5	5	0.20%	-	-	0.20	0	5	0.20%	-	-	0
D 1.8	IEQ	5	5	0.10%	-	-	0.10	0	5	0.10%	-	-	0
D 1.9	IEQ	0	5	0.10%	-	-	0	3	5	0.10%	-	-	0.06
D 1.10	IEQ	0	5	0.10%	-	-	0	3	5	0.10%	-	-	0.06
D 2.1	IEQ	0	5	0.05%	-	-	0	5	5	0.05%	-	-	0.05
D 2.2	IEQ	5	5	0.05%	-	-	0.05	3	5	0.05%	-	-	0.03
D 3.1	IEQ	5	5	0.10%	-	-	0.10	3	5	0.10%	-	-	0.06
D 3.2	IEQ	5	5	0.05%	-	-	0.05	0	5	0.05%	-	-	0
D 3.3	IEQ	5	5	0.05%	-	-	0.05	5	5	0.05%	-	-	0.05
D 4.1	IEQ	5	5	0.10%	-	-	0.10	3	5	0.10%	-	-	0.06
D 4.2	IEQ	5	5	0.10%	-	-	0.10	3	5	0.10%	-	-	0.06
D 4.3	IEQ	5	5	0.10%	-	-	0.10	3	5	0.10%	-	-	0.06
D 4.4	IEQ	5	5	0.10%	-	-	0.10	3	5	0.10%	-	-	0.06
Partial score					5.38%						0.55%		
Difference		4.83%											

*1 Urban, site and infrastructure systems, *2 Energy and Resource Consumption, *3 Indoor Environmental Quality. The system score involves multiplying the project score by the indicator weight divided by the maximum score.

4. Results

The results of the comparative evaluation by each GBRS have been the following: ASGB (2%), BEAM (12.17%), BREEAM (10.24%), CEDES (24.07%), DNGB (17.69%), GBI (4%), GG (10.5%), GS (19.09%), IGBC (9.33%), LEED (8.18%), and SBTools (4.83%) (Table 15, Fig. 14).

Table 15 Score differences between *Mariposa-bio* and *Mariposa-no-bio* for the 11 GBRS.

GBRS	ASGB	BEAM	BREEAM	CEDES	DNGB	GBI	GG	GS	IGBC	LEED	SBTools
Score *Mariposa-bio*	5.74	18.50	22.85	32.60	40.89	8.00	21.00	34.55	20.00	32.72	5.38
Score *Mariposa-no-bio*	3.74	6.34	2.76	8.53	23.20	4.00	10.50	15.45	10.67	24.54	0.55
Score difference	2.00	12.17	20.09	24.07	17.69	4.00	10.50	19.09	9.33	8.18	4.83

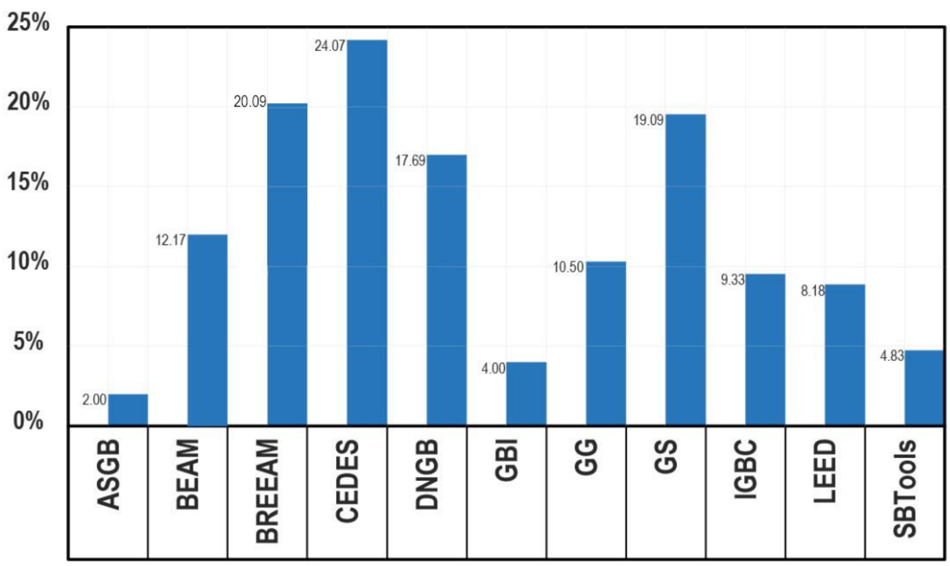

Fig. 14 Contribution of *deep bioclimatic design* to a building's sustainability level, using 11 GBRS.

5. Discussion

This study aims to quantify the contribution of deep bioclimatic design to the sustainability level of buildings in warm climates. To this end, a house incorporating *deep bioclimatic design* principles was evaluated and compared with a non-bioclimatic house using 11 of the most internationally representative *Green Building Rating Systems* (GBRS).

The *Mariposa* house exhibits a high level of bioclimatic performance, as it is capable of maintaining indoor thermal comfort without the use of heating or air-conditioning systems. Consequently, the assessment corresponds to a building with a deep bioclimatic design. It should be noted that if buildings with lower levels of bioclimatic implementation—partially dependent on energy-consuming systems—were analyzed, the sustainability scores obtained across the different GBRS would likely be lower.

All GBRS considered in this study recognized the contribution of sustainable design to the overall sustainability level of the *Mariposa* house. However, notable differences were observed among the evaluation results. Three GBRS (CEDES, DNGB, and GS) were able to more effectively capture the contribution of deep bioclimatic design to building sustainability, whereas the remaining systems assigned comparatively lower scores. In particular, three GBRS (ASGB, GB, and SBTools) reflected the benefits of deep bioclimatic design only to a limited extent, despite the documented environmental and sustainability advantages of the *Mariposa* house. This variability suggests that sustainability assessments may be influenced by the specific methodological frameworks adopted by each GBRS.

Similar observations have been reported in previous studies, which have examined the strengths and limitations of GBRS [17]. Some authors have noted that architectural design aspects are not always sufficiently emphasized within existing scoring frameworks [39-44], potentially leading to an incomplete representation of certain sustainability strategies. Other studies have highlighted the need for greater harmonization among GBRS and for a more consistent definition of sustainability, supported by comparative analyses across different rating systems [45].

Additional research has indicated that, in some cases, buildings certified under certain GBRS do not consistently demonstrate substantial energy savings or optimized resource use when compared with conventional buildings [42, 46-48]. These findings suggest that certification alone may not always guarantee improved environmental performance and underscore the importance of critically examining the indicators and weighting schemes employed by different rating systems. Furthermore, several studies have evaluated the performance of widely applied GBRS, such as LEED, reporting mixed results with respect to actual energy consumption and operational efficiency [12, 46-52]. These results highlight the need for continued assessment and refinement of existing certification methodologies.

The variability in the results obtained in the present study, together with the relatively modest weight assigned to deep bioclimatic design by several GBRS, despite its well-documented environmental benefits, points to the need for further methodological development in sustainability assessment tools.

The GBRS analyzed differ in their internal structures, scoring scales, category weightings, and indicator definitions. These differences reflect the diversity of conceptual approaches to sustainability underlying each system and may also be influenced by regional, regulatory, and market-specific factors [25]. While this diversity allows flexibility and adaptability, it may also limit comparability across rating systems.

Overall, the findings of this study suggest that current GBRS could benefit from further refinement. Advancing toward an internationally agreed definition of sustainability and the development of a shared conceptual framework may support the evolution of more comprehensive and robust GBRS capable of better capturing the contribution of bioclimatic design. In this regard, existing proposals for new and more integrative GBRS may serve as valuable reference frameworks for future developments at the international level [25].

5. Conclusions and Future Works

The aim of this study was to quantify the contribution of deep bioclimatic design to the sustainability level of buildings in warm climates. For this purpose, a house incorporating *deep bioclimatic design* principles—the *Mariposa* house—was evaluated and compared with a non-bioclimatic baseline reference house. Both buildings were assessed using 11 of the most widely recognized and internationally representative *Green Building Rating Systems* (GBRS).

All GBRS included in the analysis indicated that *deep bioclimatic design* contributes positively to building sustainability in warm climates. Nevertheless, a considerable disparity was observed among the assessment results. Three GBRS (CEDES, DNGB, and GS) adequately and consistently captured the contribution of the Mariposa House's bioclimatic design, whereas the remaining systems assigned comparatively low scores. Notably, three GBRS (ASGB, GBI, and SBTools) reflected this contribution only marginally, despite the evident environmental benefits associated with the bioclimatic design of the *Mariposa* house.

Based on the average results obtained from all 11 GBRS, the contribution of bioclimatic design to the overall sustainability level was estimated at 11.99%. In contrast, when considering only the average results of the three GBRS that yielded the highest scores, this contribution increased to 21.08%.

To further substantiate these findings, future research should include similar comparative assessments of deep bioclimatic buildings using both the 11 GBRS considered in this study and additional rating systems, in order to enhance the robustness and generalizability of the results.

Data Availability Statement (DAS)

The data that support the findings of this study are available from the corresponding author (De Garrido, Luis), upon reasonable request.

Highlights

-Contribution of deep bioclimatic design to the sustainable level of buildings;

-Capacity for evaluating bioclimatic design by current GBRS;

-Bioclimatic, sustainable and self-sufficient house;

-Zero energy buildings;

-Green Building Rating Systems.

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