［投稿論文：研究論文］

An Evaluation of Optimal Space of a 3D-Printed Scaffold for a Cricket-Breeding Module

3D プリンターによるコオロギ飼育空間最適化の評価

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Abstract: Crickets will gain importance as a future animal protein source. Optimizing the design of their living space is vital to further their mass production. To obtain data that can be used as a reference for realizing it, four types of truncated octahedron frame shelters (scaffold modules) with sides measuring 9, 11, 13, and 15 mm were created with a 3D printer. Shelters occupied most of the crickets' living space, and their preference for these frames was examined. Results found crickets tend to prefer the 9 mm scaffold module. Considering the industrial benefits of low weight, the lighter 11 mm scaffold module, with the second-highest cricket preference, is optimal for large-scale cricket farming.

コオロギは未来の動物性タンパク質源として期待されている。今後コオロギの大量生産を実現する際、コオロギの好む最適居住空間の確立が求められる。その参考となる情報を得るため、一辺が 9，11，13，そして 15mm の 4 種類の切頂八面体充填フレームを 3D プリンターを用いて制作し、それらに対するコオロギの選好性を検証した。その結果、最多となるコオロギの入居数は、最も細かい一辺 9mm の飼育モジュールにおいて記録された。しかし、軽量化による産業上の利点を考慮すると、次点の一辺 11mm の飼育モジュールがコオロギ養殖産業における至適条件であることも示唆された。

Keywords: *Acheta domesticus,* the optimal size of habitable space, truncated octahedron frame scaffold, 3D printer, large-scale cricket farms
ヨーロッパイエコオロギ、最適居住空間、切頂八面体充填フレーム構造、3D プリンター、コオロギ養殖産業

1 INTRODUCTION

The global demand for food in 2050 will be 1.6 to 2.0 times higher than that of today (Maarten et al., 2016), due to the growth of the world's population and the consequent increase in global food consumption. Therefore, the discussion on food security and production increase is urgent (Gahukar, 2011). In particular, protein nutrients are crucial for a healthy and balanced diet. Unfortunately, proteins are also the most expensive nutrient to produce in terms of the resources required (van Zanten et al., 2016). The Food and Agriculture Organization (FAO) introduced insect-based food as a possible solution to the food crisis in a published document titled *Edible Insects: Future Prospects for Food and Feed Security* in 2013 (van Huis et al., 2013).

Our current livestock industry relies on the use of large land areas, heavy consumption of energy and water, and generates considerable amounts of greenhouse gases, e.g., CO2, CH4, and N2O (Smith, 1996). To respond to those issues, edible insects were introduced as an environmentally friendly animal protein option. The impact of the FAO's paper has garnered interest from the food and agriculture industry, and it has engaged with various disciplines, ranging from social science to food science, and of course design (Aguirre et al., 2011). This research is concerned with the design of a cricket breeding system that will help the safe, efficient production of animal proteins with minimum environmental impact. According to previous studies included in this research, cricket farming proved beneficial in environmental, energetical, ethical, social, and possibly economic ways. Therefore, it is legitimate to assume that cricket meat will be one of the solutions for undernourished societies and to tackle the global food crisis. The overarching goal of this project is to facilitate the making of a healthy nutritious global society by providing a considerable amount of alternative animal proteins through cricket mass-production. In this study, the researchers investigate the possibilities for the design of an optimal breeding space for future large-scale cricket farming.

From the approximately 1,500 species of edible insects (Mlcek et al., 2014), the house cricket (*Acheta domesticus*) was chosen for this design development project for several reasons. Crickets are already established as a food ingredient in temperate, tropical, and savannah regions, and the availability of crickets is nearly global. In addition to being an edible insect for humans, crickets are a popular feed for pets, such as reptiles, fish, birds, and livestock (Straub et al., 2019). Therefore, there is a large body of research on crickets in biology, nutritional science, entomology, etc., as well as the breeding techniques used. Crickets rapidly reproduce in large numbers; the time needed to breed a batch of crickets from birth to harvest is only 4 to 6 weeks (Clifford et al., 1977). The cricket is an animal characterized by incomplete metamorphosis, therefore, the cricket farming environment requires a single condition to be maintained for the whole duration of their breeding. As crickets require only a dry environment, the maintenance of the farming facilities is simple, and can easily avoid odor problems and environmental pollution. Since cricket farming does not require any expensive facility or infrastructure, small-scale cricket enterprises, in particular, can deliver significant profit as an alternative to the regular income for local farmers (Fuah et al., 2015), while women or the elderly could easily be involved in farming operations. Domestic waste can be used as feed for the crickets, therefore, local organic waste can turn into a resource of the cricket farming industry (Bawa et al., 2020). Lastly, cricket's feed conversion efficiency is 8 times higher than that of beef, for example, and cricket proteins are characterized by high-quality nutrients. Cricket proteins achieve a good score in terms of containing essential amino acids, exceeding the standards set by the World Health Organization (Collavo et al., 2005).

The field trips for this study took place in Thailand in 2018 and 2019. In August 2018, Dr. Yupa Hanboonsong introduced the research group to the Noppadon Cricket Farm in Lopburi Province, Central Thailand. The second trip occurred in November 2019, to one of the largest cricket farms in Thailand, run by Smile Bull Marketing Co. Ltd., a company known for its famous fried cricket snacks available in many convenience stores and supermarkets in Thailand.

Generally, both the visited farms had adopted a similar method for farming, especially in cricket housing. The conventional cricket housing is built by layers of paper egg trays in a breeding box, which create hiding spaces for crickets (Fig. 1A). The layers of egg trays create numerous vertical narrow gaps that can host many crickets inside. The paper egg trays are light and cheap, making them easy to handle

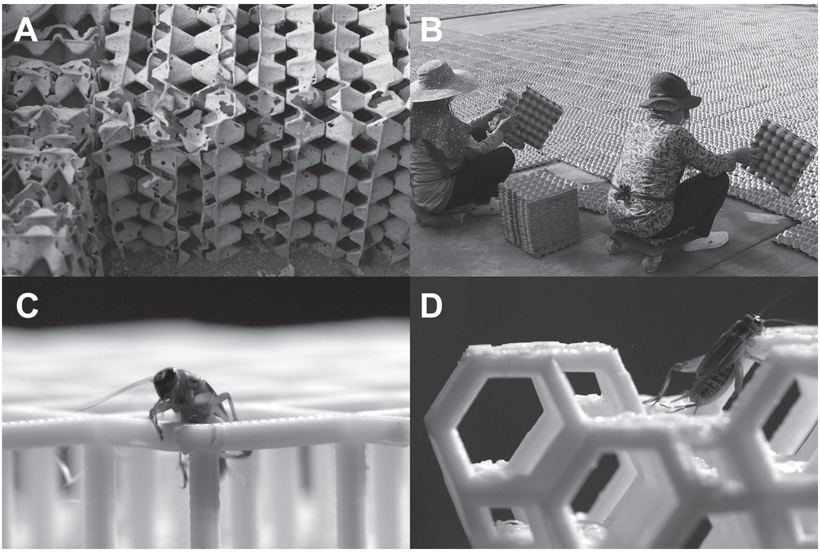

Fig. 1 A Conventional Cricket Farm and Prototypes of Breeding Modules
A) Paper egg tray for cricket housing, with holes bitten by crickets. B) The sun-drying process of current cricket housing, allowing tray reuse 2–3 times. C) In the earlier prototype of the breeding module with a square grid scaffold, the test cricket displayed discomfort in movement. D) The prototype with a truncated octahedron structure provided a smooth landscape for cricket movement. (Image source: the author).

and dispose of when dirty or damaged. This system is economically reasonable as it features good efficiency. However, the paper egg trays easily accumulate waste, such as droppings, feces, molted skin, and food leftovers on the surface. Since the layers of egg trays are not replaced until harvest, the accumulated dirt remains on the surface for a long time. Furthermore, some holes were spotted on the surface of the egg tray, because the humidity or dripping of water onto the egg trays makes the material soft and easily bitten by crickets (Fig. 1A). Normally, egg trays are reused two or three times, as farmers dry them under the sun after each harvest. The current sun drying treatment requires large areas in the farms to lay out the egg trays on the ground (Fig. 1B). In practice, there is no strict guideline to inform the right procedures for discarding the egg trays, not even in GAP[1)]. Findings from a series of observations suggest that it is essential to develop a novel cricket housing system for easier and safer hygiene control.

A 3D-printed scaffold has been developed to replace the current paper egg trays and give shape to space-filling geometry for vertical cricket housing. This study started from the result of a previous simple test, consisting of an ethological observation of the crickets' behavior. In the previous test, we compared the behavior of crickets in a space divided by a regular square grid and in a space divided by units shaped as truncated octahedrons. The movie from the previous ethological observation recorded the cricket's struggle to move in the square grid (Fig. 1C), and smooth movement in a truncated octahedron scaffold (Fig. 1D). The truncated octahedron scaffold was found to be beneficial in the distribution of the crickets within the three-dimensional space, and in facilitating their smooth movement.

From the previous ethological observations derived from the tests, the length of one side of the module determines the volume of the cell, and this directly affects the cricket's behavior. Our previous ethological observations led the researchers to notice that to provide both comfortable occupancy and movement across truncated octahedron modules, the length of each side of the cells needs to be 50–70% of the crickets' body length. This study aims to evaluate the optimal breeding space of the truncated octahedron structure in greater detail.

2 METHODS

Four different cell sizes of breeding modules were prepared for this comparative experiment. The series of breeding modules measured 162 mm in diameter and 100 mm in height, with a spatial volume of 2,060,154 cubic millimeters (Fig. 2). There were four different lengths, i.e. 9, 11, 13, and 15 mm, for the side of the breeding module's cells for the test crickets (Fig. 3), which covered the ideal range of sizes since the body size of the test crickets was an average of 20 mm. This comparative experiment with four types of breeding modules was carried out in a round-robin tournament fashion, between two modules with 100 test crickets. This comparative experiment relied on the recording of the number of test crickets inhabiting each differently sized module.

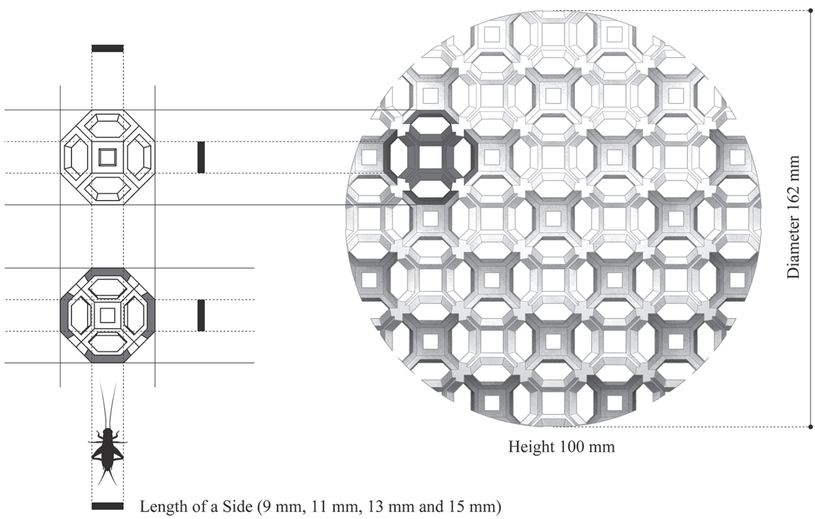

Fig. 2 Drawing of the Breeding Module in Comparison with Cricket's Body Size
There were four different lengths, i.e. 9, 11, 13, and 15 mm, for the side of the breeding module's cells for the test crickets. (Image source: the author).

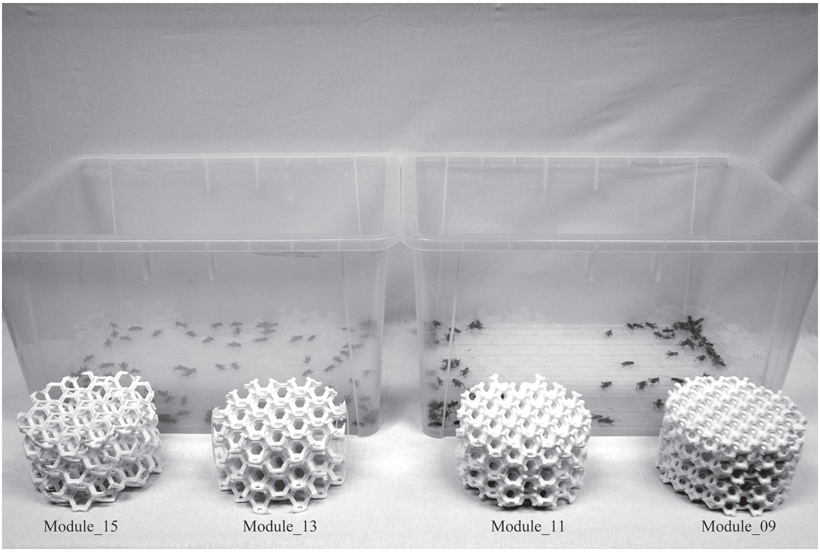

Fig. 3　Four Types of 3D-Printed Breeding Modules for Comparative Experiment
Each module was named Module_09, Module_11, Module_13, and Module_15, indicating that the length of each side of the cell was 9, 11, 13, and 15 mm, respectively. (Image source: the author).

2.1　The Flow of the Comparative Experiment

We used nearly 500 healthy adult European house crickets, with a body size averaging 20 mm long. Four types of 3D-printed breeding modules formed as truncated octahedron scaffolds were used, with a size of 162 mm diameter and 100 mm height. Each module was named as 'Module_09', 'Module_11', 'Module_13' and 'Module_15', indicating that the length of each side of the cell was 9, 11, 13, and 15 mm, respectively. Three plastic containers with dimensions of 335 mm for the inner width, 490 mm in length, and 285 mm in height were used, with a spatial volume of 46,782,750 cubic millimeters. An A3 plastic sheet was used as a space divider for easier cricket count. Additionally, a fixed-point observation camera, electric heater, air circulator, etc., were used.

As a priority, the test crickets needed to be kept healthy during the experiment. One of the plastic containers contained a resting colony that was filled with soil and layers of egg trays that created a comfortable hiding space for the test crickets. The room's environmental conditions were kept stable and comfortable for the test crickets, with the temperature kept at 30–33 °C using an air conditioner, electric heater, air circulator, and constant lighting conditions. One hundred healthy test crickets were then released into the plastic container. The plastic container was gently tilted to bring the test crickets to the edge, then positioned back to horizontal, and carefully located between two test breeding modules in the plastic container immediately. This action ensured the test crickets were not accidentally crushed under the breeding module. Both breeding modules needed to be evenly distanced from both sides of the walls (Fig. 4). The crickets were then left quietly for 20 minutes until they hid and settled into the breeding modules. After a further 20 minutes, the interior space of the plastic container was carefully and quietly divided in half by plastic sheets. A photograph of both sides of the space was taken and the number of 'non-resident crickets' was counted and categorized as 'A', which were outside of the

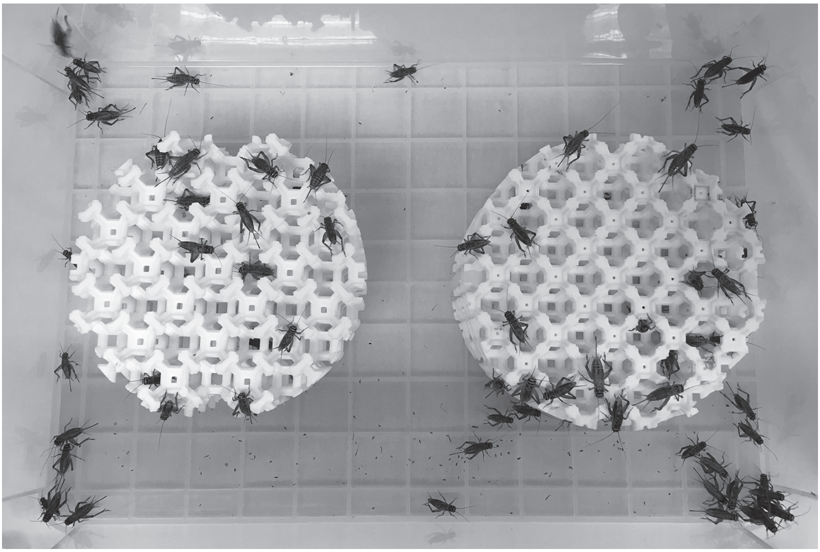

Fig. 4 The Breeding Modules in Position
Both modules were located evenly distanced from the wall of the plastic container. (Image source: the author).

test breeding modules. Each test breeding module was then gently shaken to encourage all inhabitants out into each divided space. Another photograph of both spaces was taken and the total number of all crickets was counted, and this number was referred to as ‘B’. The actual number of inhabitants of the breeding module was calculated by subtracting the number of ‘A’ crickets from the number of ‘B’ crickets. After repeating the comparative experiments three times without changing test crickets, except as a replacement in cases of death, then all crickets were brought back to the resting colony. At this point, another hundred healthy test crickets were chosen for further experiment. To avoid potential environmental bias brought about by smell or dirt from the previous crickets, the floor of the plastic container was cleaned before another hundred test crickets were introduced. All the 12 combinations of round-robin comparative experiments were repeated 10 times, to obtain reliable averageable data. This required 120 sessions in total.

2.2 Evaluation

For defining a winning evaluation level, the margin of victory was quantified in Table 1. This evaluation score was the calculation of the loser’s number of inhabitants divided by the winner’s number of inhabitants. A victory with a large margin was rated as five stars (*****), while a victory with a small margin was rated with one star (*) and scored zero (0) for a draw. Margin definitions are defined in Table 1.

Table 1 Definition of Winning Evaluation
The winning evaluation was defined across five levels.

Loss/Win	Winner’s Mark	Loser’s Mark	Evaluation
L/W ≦ 0.5	* * * * *	- - - - -	5 Star Winning
0.5 ＜ L/W ≦ 0.6	* * * *	- - - -	4 Star Winning
0.6 ＜ L/W ≦ 0.7	* * *	- - -	3 Star Winning
0.7 ＜ L/W ≦ 0.8	* *	- -	2 Star Winning
0.8 ＜ L/W ≦ 0.9	*	-	1 Star Winning
0.9 ＜ L/W ≦ 1	o	o	Draw

3 RESULTS

3.1 Comparative Pre-Experiments

Before starting the main comparative experiment, a comparative pre-experiment was carried out to find the environmental bias of the left and right sides of the plastic container. The comparative pre-experiments used the same breeding modules to compare the results between modules in the left and right sided positions. The process of the comparative pre-experiments was the same as discussed in in the methodology section. The results (Fig. 5) were rather random and demonstrated there were different environmental conditions between the left and right sides of the plastic container. As such, for reliable results, the main comparative experiment was tested in both left and right positions, to obtain reliable averageable data.

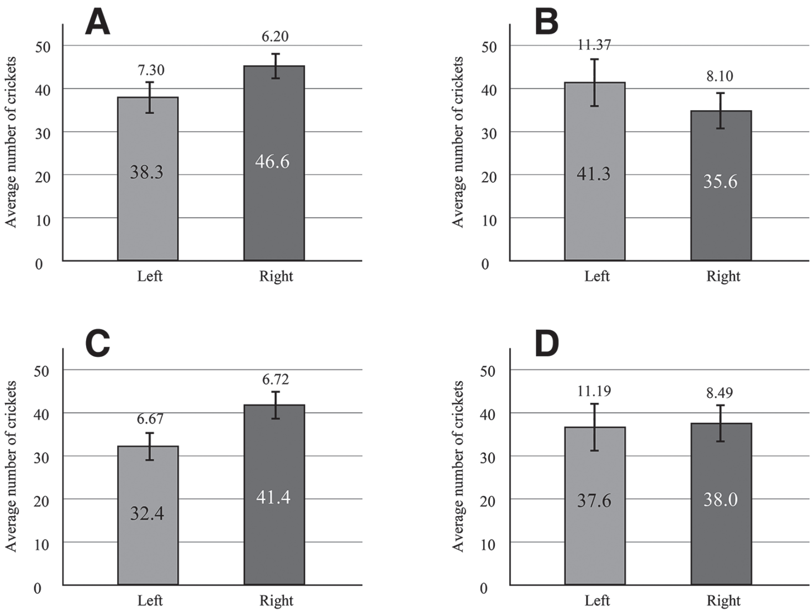

Fig. 5 The Result of Comparative Pre-Experiments

In a comparative pre-experiment, the popularity of each modules on the left and right sides of the container were examined. A represents the result of Module_09, B for Module_11, C for Module_13, and D for Module_15. Standard deviation is indicated in each result. Results were random, therefore the environmental conditions on the left and right sides of the plastic container were not even.

3.2 Evaluation by Crickets’ Behavior

The results of the main comparison experiment presented clear rules, orders, and tendencies. The total average inhabitation rate of the test breeding modules reached 76.9 %. The test crickets had a very low mortality rate of 0.09 %, with 11 deaths out of a total of 12,000 test crickets during a total of 120 sessions.

The results of all round-robin tournaments in the comparative experiments are shown in Table 2. The numbers in this table refer to the average number of inhabitants in the breeding module, out of 10 sessions. The numbers in the dark grey box indicate the modules that are positioned to the right inside the plastic container, while the numbers in the white box represent the left position, during the comparative experiments.

The results were well ordered, for example, the modules with smaller cells prevailed against the larger sizes, except in only one case in session #6. However, regardless of whether they were positioned on the left or right, the results indicated the modules with smaller cells were preferred by the test crickets. One of the great noticeable results was the overwhelming victory of Module_09 (right) against Module_15 (left) in session #4. Module_09, which contained the smallest cells, had

Table 2 The Result of the Comparative Experiments

The numbers in this table refer to the average number of inhabitants in the breeding module, out of 10 sessions. The numbers in the dark grey box indicate the modules that are positioned to the right inside the plastic container, while the numbers in the white box represent the left position. Results clearly demonstrate that smaller cell modules prevailed against their larger-celled opponents in all sessions, except session #6, which was more even.

<table>
<tr><th>Right
Left</th><th colspan="2">Module_09</th><th colspan="2">Module_11</th><th colspan="2">Module_13</th><th colspan="2">Module_15</th></tr>
<tr><td rowspan="2">Module_09</td><td colspan="2" rowspan="2"></td><td colspan="2">session #7</td><td colspan="2">session #8</td><td colspan="2">session #9</td></tr>
<tr><td>42</td><td>41</td><td>50</td><td>36</td><td>50</td><td>28</td></tr>
<tr><td rowspan="2">Module_11</td><td colspan="2">session #1</td><td colspan="2" rowspan="2"></td><td colspan="2">session #10</td><td colspan="2">session #11</td></tr>
<tr><td>34</td><td>46</td><td>46</td><td>33</td><td>45</td><td>24</td></tr>
<tr><td rowspan="2">Module_13</td><td colspan="2">session #2</td><td colspan="2">session #3</td><td colspan="2" rowspan="2"></td><td colspan="2">session #12</td></tr>
<tr><td>23</td><td>54</td><td>26</td><td>48</td><td>39</td><td>29</td></tr>
<tr><td rowspan="2">Module_15</td><td colspan="2">session #4</td><td colspan="2">session #5</td><td colspan="2">session #6</td><td colspan="2" rowspan="2"></td></tr>
<tr><td>21</td><td>55</td><td>26</td><td>50</td><td>39</td><td>38</td></tr>
</table>

over 2.5 times more inhabitants on average than Module_15 which contained the biggest cells. In session #7, Module_09 also narrowly outperformed Module_11 which contained the second smallest cells. Results, therefore, indicate that the gap of the cell size affected the level of scores.

Table 3 shows the compiled data; results show that modules with smaller cells prevailed against their opponents in the round-robin testing. The strongest and smallest cell size, Module_09, won three times against all other modules. The second smallest cells, Module_11, won twice; Module_13 won once, and Module_15, which contained the biggest cells, lost all of its comparative matches. The winning evaluation level was high when the gap of cell size was large, for example, Module_09 scored five stars (*****) against Module_15 (Table 3). Furthermore, the winning evaluation level was low while the gap of cell size was narrow, for example, Module_09 scored a single star (*) by winning against Module_11, as did Module_13 which scored (*) against Module_15. Interestingly, Module_11 scored three stars (***) against Module_13, which was not as narrow as other results in close size gap combinations. Many cricket inhabitants found an individual space for themselves,

Table 3 The Final Result of Comparative Experiments
Combined final data from Table 2. Results show Module_09 to be the clear winner against all other module sizes.

	Module_09	Module_11	Module_13	Module_15	Number of Wins
Module_09		44 (vs 38) 0.86 *	52 (vs 30) 0.58 * * * *	53 (vs 25) 0.47 * * * * *	3
Module_11	38 (vs 44) -		47 (vs 30) 0.64 * * *	48 (vs 25) 0.52 * * * *	2
Module_13	30 (vs 52) - - - -	30 (vs 47) - - -		39 (vs 34) 0.87 *	1
Module_15	25 (vs 53) - - - - -	25 (vs 48) - - - -	34 (vs 39) -		0

claimed their own territory in a single cell, and remained there for a long time, especially in Module_09 and Module_11. On the other hand, the bigger cells in Module_13 and Module_15 contained multiple crickets in a single cell and allowed trespassers to cross the space already occupied by other crickets. Therefore, Module_09 and Module_11 provided high livability, while Module_13 and Module_15 provided livability and high mobility at the same time.

4 DISCUSSION

4.1 Discussion in Entomological Aspect

Firstly, the comparative experiment presented clear, definitive quantitative results. It is very rare to find studies that combine cricket behavioral research with breeding space design. The behavior of crickets has been scientifically investigated through neurobiological studies (Mallory et al., 2016). However, such studies don't usually investigate the relationship between the crickets' preferences and the quality of space. In 1976, a simple cricket behavioral experiment was carried out that featured both qualitative and quantitative aspects in the study; its approach was similar to ours. The 1976 study examined cricket ethology in a terrarium with tubes and a resting colony. The results of this study demonstrated that crickets preferred narrower and darker tubes and places for resting since crickets are mostly photo-phobic and shelter in humid, dark places (Kieruzel, 1976). This characteristic of the crickets is clearly reflected in the results of our comparative experiments. The most popular breeding module was the densest one, Module_09, which offers narrower and darker spaces inside, which in turn attracted many test crickets during the experiments. In contrast, our experimental room was bright because of the intention of keeping clear visibility for monitoring purposes. This bright environment persuaded the test crickets to choose one of the breeding modules to hide. There seems to have environmental bias between two positions in the plastic container, as Table 1 shows; however, the characteristic of photophobicity forced the crickets to choose the right breeding modules to hide during the comparative experiments. The accuracy of the crickets' selection was successfully observed through the comparative experiments.

There exists an interesting behavioral study tracking cricket movement in two dimensions using sensors, video analysis, and identifying tracking (Kaláb et al., 2021). The technology for tracking cricket movements is well developed in this study, however, the space used for such tracking studies only operates across the horizontal dimension, to favor scientific rigor. However, the real potential in this study is that the same methodology and technology can be applied in our 3-dimensional study featuring truncated octahedron scaffolds in the future.

It is also said that crickets like to climb, so it is important to vertically maximize the available housing surface for better industrialization (van Huis and Tomberlin, 2017). Since the relationship between cricket behavioral analysis and space design has rarely been examined since 1976, our methodology of conducting comparative experiments using truncated octahedron scaffolds has a great value in this field today.

4.2 Space Design Aspect

Since there were dense numbers of inhabitants in the breeding modules during the comparative experiments, what we are studying is a design of the housing complex for the crickets; simply put, spaces that can accommodate a density of inhabitants to shelter them efficiently. In architectural history, the modernization of building design and urban planning was developed when the human population rose greatly after the industrial revolution. The Swiss-French architect Le Corbusier, who modernized and standardized building design to meet the emerging needs of a growing population, displayed the Modulor, which shows a relationship between the architectonic space and the human body (Le Corbusier, 1967). Most importantly, the achievement of the Modulor is that the standard can be applied in any city, any region, and for any religious background, globally. As with the Modulor, the methodology for building a cricket breeding module is repeatable geometry and space-filling cells, that create constant regular 3-dimensional patterns that waste no space. Our investigation started with specific species of cricket, the European house cricket (*Acheta domesticus*), which is smaller than other popular edible crickets in the world. One of the most important achievements through this study is the evaluation of the habitable space in comparison to the cricket's body size. It has discovered a strong relationship between body length and volume of space. If the Modulor of the cricket-breeding world proves successful, then it can be applied in any type of cricket in any region of the world.

Our study is focused on the adult European house cricket with an average body length of 20 mm. There are many species of edible cricket in the world with varied average body sizes; as such, the breeding modules need to be modified locally for the worldwide industrialization of cricket farming. Three-dimensional data of the truncated octahedron scaffold can be easily modified by local farmers, designers, or engineers, and affordably 3D printed at local institutes in any region. Further optimization for different species of cricket can be done locally, remotely, and without geographical limitations. Our 3D data of the breeding module will be an open-source resource, so engineers, designers, and farmers can access it from any region, aiding more accurate locally-adapted optimization of cricket housing in the future (Singh et al., 2011).

4.3 Industrial Aspect

The conventional large-scale livestock industry, such as the one for cattle, pigs, and poultry, is accurately defined by a scale ratio between the breeding space/volume and the amount of harvest (Hlavarty and Krejci, 2020). Also, the scale of initial investment, equipment, facility, maintenance, labor cost, energy consumption, feeding, and handling are optimized through the process of industrialization. However, the cricket farming industry has not yet reached such a level. The results of this experiment need to be considered in terms of industry, as well as cricket preference. The weight of the product is one of the most important factors in industry (Beukers and Hinte, 2001), for example, heavy modules consume more material, time, and energy during production and transportation, and can impose handling difficulties during the production process as well as on the farm.

The data about the build statistics of the breeding modules are extracted from the program ‘Simplify3D’ for 3D printer (Table 4), with data being digitally calculated and highly reliable. As the size of the cells decreases, the density of internal space becomes higher and the breeding module’s weight also increases. For example, while Module_09 features the best score in Table 3, it is the heaviest module (Table 4), and costs 2.6 times the price of Module_15, the lightest one, while being 2.6 times the weight.

To effectively balance the ratio between the cricket preference and the industrial requirements, Fig. 6 represents the weight of each module per cricket capita. The lighter module is considered more efficient than its opponents, according to the aspect of industrial advantage; its reevaluation in terms of industrial preferences has resulted in an interesting development. The bars highlighted in pale gray score lighter, which is considered better in terms of the industrial approach. As seen in Fig. 6, the module with the best industrial results is Module_11, with three scores, which is lighter than several opponents. Surprisingly, Module_09 which gained the best score in Table 3 scored the worse in terms of industrial aspects (Fig. 6). Finally, Module_11 performed excellently in the comparative experiment, being successful both in terms of its industrial benefits and cricket preference. Apart from having the lower number of inhabitants, Module_15 scored 3.79 g, the best total average of weight per cricket capita (Fig. 6). Module_09, the most preferred module according to cricket choice, but the worst by industrial merit, still presents the chance to perform a greater number of harvests. This is because this study did not explore habit observation, such as territory claim and cannibalism, in higher densities over a longer period.

Table 4 The Data of Build Statistics of Each Breeding Module for 3D Printing
Data were extracted from Simplify3D and showed the densest module, Module_09, was the heaviest and the most expensive to produce.

Module	Build time (minutes)	Plastic weight (g)	Filament length (mm)	Material cost (USD)
Module_09	1,228	272	90,417	13
Module_11	838	183	60,705	8
Module_13	610	128	42,579	6
Module_15	503	104	34,446	5

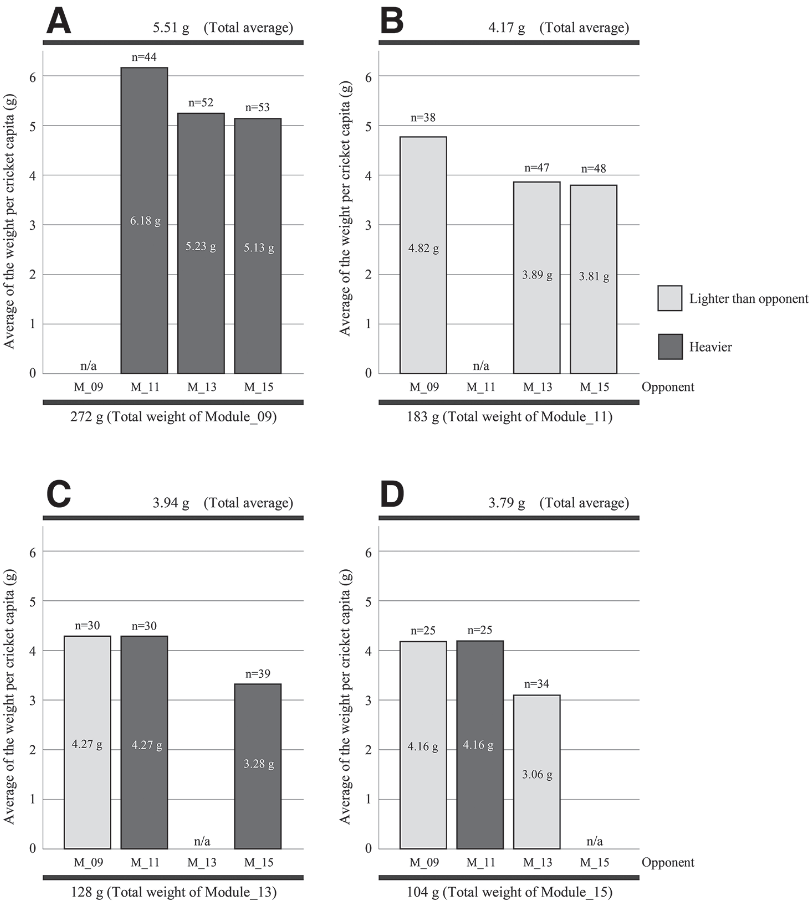

Fig. 6 The Result of Module Weight per Cricket Capita

A represents the result of Module_09, B for Module_11, C for Module_13, and D for Module_15. Module_11, which is second place in Table 3, achieved an excellent result after the analysis of the relationship between its weight and its cricket population. 'g' represents the weight per cricket capita. 'n' represents the number of crickets in the population. Pale gray columns represent a module that is lighter than its opponent in the comparative experiments. Lighter models are considered a better fit for industrial application.

Endnotes

1) As the cricket industry has grown rapidly in Thailand in recent years, the GAP (Good Agricultural Practices for Cricket Farm, November 2017) has been enforced (National

Bureau of Agricultural Commodity and Food Standards, 2017). The GAP is a protocol aiming at standardizing the cricket farming know-how that was developed independently through the local farmers' own past experiences. Since the GAP was made public, the cricket industry has gradually solidified for further growth in Thailand. More recently, an English version has been made available (Hanboonsong and Durst, 2020).

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