Journal of Emerging Technologies and Industrial Applications
Vol. 4 No. 2 (2025) pp. 1-7
e-ISSN: 2948-507X

Journal homepage: https://jetia.mbot.org.my/index.php/jetia/index

Next-Gen Stingless Bee Traps with 3D Fabrication for Smart Agriculture Solutions

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Abstract: Pollinators such as bees are vital to global food security, with approximately 75% of food crops depending on pollination. However, colony collapse disorder (CCD), driven by climate change, habitat loss, and improper bee trap handling, has severely impacted bee populations. This study introduced a smart farming solution through the development of a new stingless bee trap (NSBT) designed to minimise human intervention and enable real-time remote monitoring. A user-needs survey involving small-scale stingless beekeepers informed the design process, with data analysed and translated into technical specifications through the House of Quality (HOQ) framework. The prototype was fabricated using biodegradable polylactic acid (PLA-F) through 3d printing. The NSBT integrated Arduino Iot recorded environmental data, with temperature and humidity ranging from 32.5°C to 34°C (SD between 0.4°C and 0.6°C) and mean humidity level from 88% to 85.5% (SD between 1.2 – 1.5), indicating both parameters are in stable conditions. A Business Model Canvas (BMC) and cost evaluation were developed to assess commercialisation potential for small-scale beekeepers. The NSBT combines 3d-printed fabrication, smart sensing and user-centric design, exemplifying smart farming practices supporting Sustainable Development Goals (SDG) No. 2, Zero Hunger, and SDG No. 13, Climate Action.

Received 15 June 2025;
Accepted 21 September 2025;
Available online 28 December 2025

Keywords: Arduino IoT, colony collapse disorder, stingless bee, 3D printed trap, smart farming.

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1. Introduction

Colony collapse disorder (CCD) is a phenomenon characterized by the sudden and unexplained disappearance of worker bees from a beehive, leading to the collapse of the colony. CCD was first identified in 2006 in North America, where beekeepers reported unusually high losses of bees without any apparent cause [1]. The importance of resolving CCD cannot be overstated, as it poses a significant threat to global food security by disrupting the vital role of bees as pollinators. Approximately 75% of global food crop types depend on pollinators, thus, their disappearance may cause serious negative effects on the environment and economy [2].

CCD arises from the combined effects of many contributing factors, such as climate change, habitat destruction, and internal factors like stress induced by stingless bee trap manipulation [1,3]. This study aimed to mitigate the effects of CCD by introducing a new trap design for stingless bees to minimise human intervention and reduce stress on the colony. The stingless bee was selected due to occupational safety and health considerations, as they are naturally stingless, making them safer to handle. The improved bee trap design aims to align colony well-being and survival with economic gain, supporting sustainable apiculture practices through smart farming innovation.

Supporting swarm capture and nesting is the main objective of stingless bee trap designs, taking into consideration their ecological impact. Poorly constructed traps or excessive usage in delicate areas may negatively impact the local bee population and their habitats [4-5]. Fig.1 illustrates the common practice of repurposing empty plastic cooking oil bottles as stingless bee traps.

Fig.1- Plastic bottles reused as stingless bee traps hung on trees to attract new queens [4]

Using traps is a sustainable approach to expanding stingless bee farming without cutting down trees to obtain new bee colonies. Once the stingless bee queen enters the trap, she establishes her nest and starts building the colony. This newly formed colony can be transferred into an empty hive as their new home for breeding and producing honey [4-5].

2. Materials and Method

Users' experience with the traditional stingless bee trap (TSBT) was gathered through online interviews with 10 experienced stingless beekeepers with more than one year of experience and managing at least ten hives. These sessions were conducted via the Google Meet platform, guided by a structured Google form prepared to streamline the interview process and record their feedback on demographics, experience, trapping method, species captured, survival rate, and causes of colony death. Additionally, the interview also included questions on trap usability, the queen transfer process, and overall satisfaction. The insights obtained were used to develop the House of Quality (HOQ) for the New Stingless Bee Trap (NSBT), translating customer needs into actionable technical requirements. Next, a Business Model Canvas (BMC) was constructed to evaluate the technical viability, economic sustainability, and scalability of the NSBT in real-world applications.

The AutoCAD software was used to create detailed three-dimensional (3D) technical drawings, as well as to generate the Bill of Materials (BOM) for the NSBT. The finalized NSBT model was fabricated using a Creality Ender-5 3D printer.

An Arduino-based was developed to enable real-time environmental monitoring. The setup incorporated a DHT22 sensor integrated with an Arduino MKR WiFi 1010 board, allowing for the measurement and wireless transmission of temperature and humidity data. The system was connected to the internet and interfaced with an IoT cloud platform, enabling continuous data processing and remote monitoring via a dashboard.

Finally, the NSBT prototype was installed at the IIUM Kelulut Sanctuary located on the Gombak campus, in Kuala Lumpur. The system was monitored for four months using the Arduino-based setup. This is among the pioneering efforts to explore the performance of 3D-printed traps combined with real-time data monitoring.

3. Results and Discussions

3.1 TSBT Model

Fig. 2 presents a close-up view of reused plastic bottles repurposed as single-use stingless bee traps. Beekeepers typically fabricate these traps manually or purchase them from online platforms at an approximate cost of RM15 each [6].

Fig.2- Close-up view of self-made TSBT by author

A nozzle was positioned at the centre of the trap to serve as an entrance for the queen bee and as a ventilation outlet. Following the installation of TSBT, frequent manual inspections were necessary to determine whether a new queen had been successfully captured. If the queen was not promptly transferred to a hive, she faced a high risk of predation [4-5]. Once a queen was found inside TSBT, the trap had to be cut open for manual transfer, rendering it unusable and subsequently discarded as

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waste. This process required substantial human intervention, potentially stressing the newly established colony and compromising its chances of survival.

3.2 Interviews Data

Fig. 3 represents the beekeeper's geographical distribution. All respondents were Malay males, aged between 37 and 60 years. Of the participants, 60% had more than 10 years of beekeeping experience, while the remaining 40% had between 1 to 5 years of experience. In terms of geographical distribution, 60% of the beekeepers were based in the Klang Valley. The remaining participants operated in Kota Tinggi, Johor, Lenggeng Ulu Bendul, Negeri Sembilan, and Bentong, Pahang, with each location representing 10% of the total respondents.

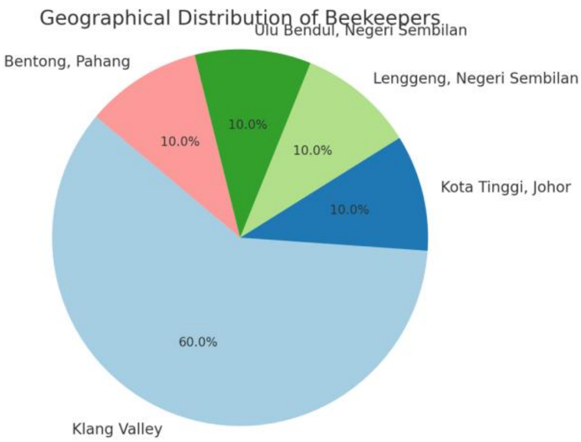

Fig.3- Geographical distribution of beekeepers

All respondents unanimously agreed that their primary motivation for using TSBT was to support the sustainability of wild bee populations and to conserve trees that serve as their natural habitats. This is an interesting finding of very good environmental literacy among local beekeepers. A study by [7] involving 180 beekeepers in Ethiopia found that beekeeping remains a male-dominated activity and highlighted that awareness levels among beekeepers significantly influence the adoption of improved beekeeping technologies.

Table 1 presents the feedback gathered, showing *Heterotrigona itama* was the most commonly captured species with a success rate of 80%. Other species, such as *Tetragonula. Leaves, T. terminata, T. fuscobalteata, and T. collina* were captured at lower rates, each accounting for approximately 10%. These species are resin-dependent but exhibit greater adaptability, as they are capable of collecting resin from a variety of plants, including fruit trees commonly found in agricultural or peri-urban settings [8]. In contrast, dammar-dependent species, typically reliant on *Dipterocarpus* spp. for resin, were not recorded. This absence is likely attributed to the fact that all participating beekeepers operated in locations devoid of *Dipterocarpus* trees, usually found in tropical forests such as balau and meranti [9].

Table 1 – Species captured and survival rates using TSBT

Responses	Species captured	Colony Survival
20%	*H. itama*	2 years 12 months
40%	*H. itama* *T. leaveceps* *T. terminata*	6 months 3 months
40%	*T. fuscobalteate,* *T. collina*	1-2 months

All respondents employed a similar trapping method, installing TSBTs during the dry season, which typically spans from May to September [10]. This timing resulted in comparable queen capture waiting periods, generally four to six weeks.

Table 1 also indicates that the survival duration of new colonies varied according to species, with the longest lasting up to 2 years (10%), 12 months (10%), 3 to 6 months (40%) and the shortest surviving between 1 to 2 months (40%). Respondents' inputs on the causes of colony failure included pest and predator attacks, colony weakness due to improper trap handling such as rough cutting or shaking during queen transfer, insufficient bee workers, heat exposure during hot seasons and inadequate resin availability for colony sealing and defense. Similar challenges were reported by studies on trap nests conducted in the Amazonas region of Brazil and the University of Sao Paulo [4-5], and in Addis Ababa, Ethiopia [7].

All respondents highlighted usability concerns with TSBTS, particularly their susceptibility to invasions by ants, spiders, and frogs through the exposed nozzle design. Additionally, the lack of structural protection made the traps vulnerable to monkey attacks. These design flaw requires frequent monitoring and maintenance. These vulnerabilities are consistent with findings by [4], which recorded the presence of non-target species in 157 trap-nests (72%), supporting the need for more secure and resilient trap solutions.

Additionally, 70% of respondents stated that the queen transfer process was laborious and time-consuming, while the remaining 30% accepted it as it is due to familiarity and lack of better alternatives. In term of user satisfaction, 60% of respondents expressed dissatisfaction with the poor ventilation of TSBTS, which led to heat buildup and weakened both the queen and her small colony. This concern aligns with findings by [5] who reported the death of a colony consisting of 245 workers and a virgin queen inside a plastic trap-nest due to excessive moisture accumulation, highlighting the detrimental impact of inadequate microclimate regulation within trap designs.

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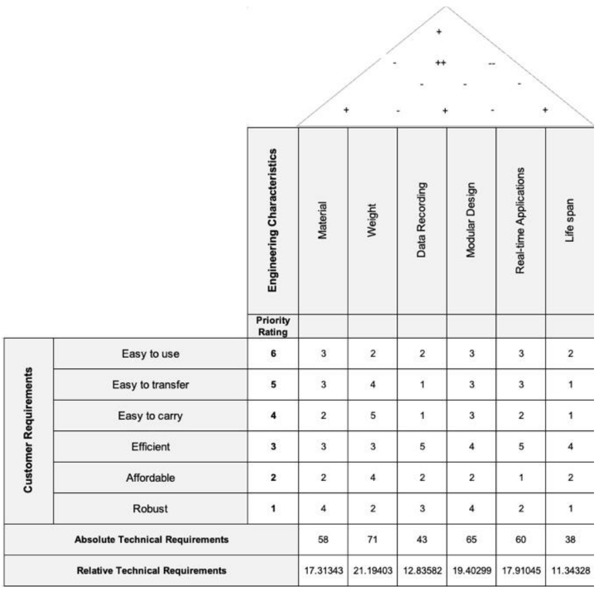
Meanwhile, 30% of respondents suggested finding new material, and another 10% recommended improving the TSBT design.

3.3 House of Quality (HOQ)

The HOQ in Fig. 4 was developed based on feedback from interviews with experienced stingless beekeepers, which are instrumental in identifying the limitations of TSBT and understanding customer needs, prioritising them and integrating them into the product development of NSBT [11] .

The most critical engineering characteristics in Fig. 4 are weight (21.19) and modular design (19.40), followed by real-time applications (17.91). This HOQ is in line with the functional requirement of the trap, which was designed to be hung on a tree trunk. The combination of lightweight and modular design is critical, as the light trap is easier for beekeepers to handle, reduces installation effort, and minimises the risk of falling. Meanwhile, modularity allows for easier inspection, maintenance, and separation of brood and honey sections, reducing colony disturbance and improving long-term trap usability.



Customer Requirements	Priority Rating	Material	Weight	Data Recording	Modular Design	Real-time Applications	Life span
Easy to use	6	3	2	2	3	3	2
Easy to transfer	5	3	4	1	3	3	1
Easy to carry	4	2	5	1	3	2	1
Efficient	3	3	3	5	4	5	4
Affordable	2	2	4	2	2	1	2
Robust	1	4	2	3	4	2	1
Absolute Technical Requirements		58	71	43	65	60	38
Relative Technical Requirements		17.31343	21.19403	12.83582	19.40299	17.91045	11.34328

Fig.4- NSBT's house of quality

This HOQ guided the subsequent phase of prototype development and engineering specifications with the aim of ensuring the design is both usable and marketable [11].

3.4 Business Model Canvas (BMC)

Insights into market demands were gathered through interview sessions as the participants from micro and small enterprises engaged in the stingless beekeeping industry. Their perspectives were instrumental in shaping the BMC in Fig. 5, reflecting the user-centric innovation process advocated by [12], which emphasizes empathising with end users, precise problem identification and the rapid prototyping of solutions that meet their needs.

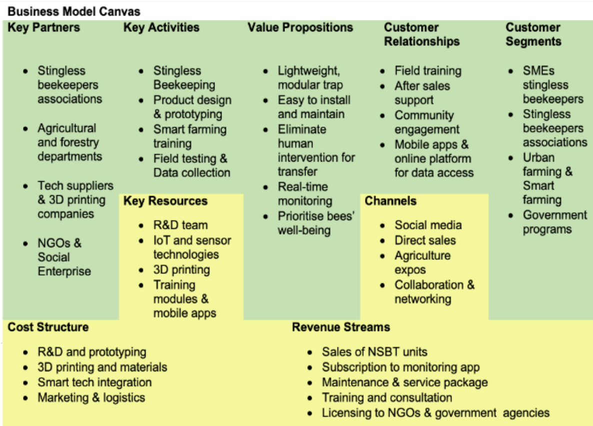


Fig.5- Business Model Canvas for NSBT

Building on the case study by [12], which highlights how a local small business owner who leveraged personal expertise and deep community insight to reinvent in public well-being, the BMC in Fig. 5 offers a value proposition of a smart farming solutions through a lightweight modular trap design integrated with Iot-enabled sensing, prioritising bee colony well-being and sustainable management. The solution targets micro and small-scale stingless beekeepers to modernise their practices. Key activities include co-designing with end-users to ensure usability and relevance, along with real-time environmental data collection to support informed decision-making.

3.5 3D Printed NSBT Prototype

AutoCAD software was utilized to produce three-dimensional (3D) technical drawings of NSBT as shown in Fig. 6. The circular shape resembles natural nesting holes and black exterior to replicate the dark interior of a tree trunk, enhancing queen attraction to enter the trap [4]. The modular configuration, which separates the brood chamber, dedicated to the queen's dwelling, from the upper section of NSBT, is intended to minimize colony disturbance during transfers to promote better colony survival [5].

Polylactic acid (PLA) was selected as the printing material due to its lightweight properties and excellent insulating characteristics, which help maintain a stable microenvironment inside the trap [13]. Fused Deposition Modelling (FDM) 3D printing technique was employed using the Creality Ender-5 printer. PLA with a diameter of 1.75 mm was melted and extruded through a 0.4 mm heated nozzle, forming fine beads that were layered to construct the components, as illustrated in Fig. 7.

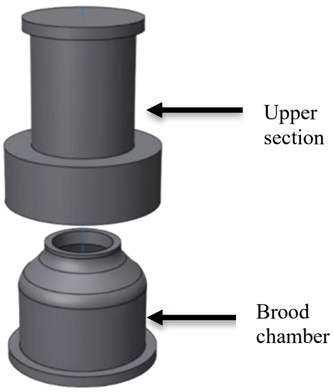
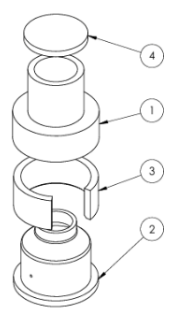


Fig.6- 3D modular design of NSBT

Fig.7- PLA-F 3D printed NSBT using FDM technique

To support the assembly of NSBT, a detailed Bill of Materials (BOM) was prepared, illustrated in Fig. 8. The structured BOM is particularly beneficial for small-scale farmers engaged in smart farming initiatives, as it ensures easy adoption and scalability [14].



ITEM NO.	PART NUMBER	DIMENSIONS(MM)	QTY.
1	Honey Chamber	H: 95.7	1
		TOP HOLE WIDTH: 48.0	
		BOTTOM HOLE WIDTH: 81.0	
		THICKNESS: 8.0	
2	Brood Chamber	H: 78.0	1
		SIDE HOLE WIDTH: 15.0	
		TOP HOLE WIDTH: 48.0	
		BASE WIDTH : 98.0	
3	Chamber Holder	H: 41.0	1
		WIDTH: 98.0	
4	Upper Honey Chamber	H: 16.0	1
		TOP WIDTH: 74.0	

Fig.8- BOM for NSBT

FDM is an affordable 3D printing technique, making it highly accessible for smart farming and beekeeping initiatives [13-14].

3.6 Environmental Data from Arduino Dashboard

In smart farming, IoT sensor technology and systematic data collection are crucial for maintaining accurate records and enabling real-time monitoring, supporting informed decisions to enhance farming efficiency [14]. Table 1 summarises environmental data recorded by the Arduino system installed in NSBT for four months at IIUM Kelulut Sanctuary.

The mean temperature recorded between 32.5°C to 34°C, with a relatively low standard deviation (SD between 0.4°C and 0.6°C), indicating stable temperature conditions across these months. Compared to Malaysia's average outdoor temperature (26°C to 32°C) from July to October 2024 [10]. This increase suggests significant internal heat retention, likely due to material insulation and reduced airflow in the NSBT [5].

Table 2 – Mean and standard deviation (SD) for temperature (temp) and humidity

Month	Mean Temp (°C)	Temp SD	Mean Humidity (%)	Humidity SD
July	34.0	0.6	88.0	1.5
August	33.5	0.5	87.0	1.4
September	33.0	0.4	86.0	1.3
October	32.5	0.4	85.5	1.2

Similarly, the mean humidity levels inside NSBT ranged from 88.0% to 85.5%, slightly decreasing over time but consistently higher than Malaysia's average ambient humidity of 84% [10]. The SD was also low (SD 1.2 – 1.5), reflecting stable but elevated internal moisture levels. This excess humidity may be attributed to limited airflow and moisture from stingless bees [5]. A study conducted at Universiti Teknologi Malaysia, Johor Campus reported that the internal hive conditions for *H. itama* showed relative humidity levels fluctuating between 70% and 85%, with the temperatures consistently exceeding 30°C [15]. These high values indicate the bees' sensitivity to microclimatic stability for colony health.

Another researcher at Multimedia University, Cyberjaya, performed real-time remote monitoring using LoRa technology, revealing indoor temperature ranging from 30.13°C to 33.62°C, and indoor humidity levels between 63.6% and 73.15% [16]. These findings highlighted the importance of precise environmental regulations in stingless bee management and the potential of IoT-based systems for safeguarding colony welfare under variable tropical conditions.

3.7 Cost Evaluation

The study performed a cost evaluation between NSBT and TSBT to assess economic feasibility and potential advantages in terms of material, maintenance and long-term usage [11]. Table 1 summarises a comparison between TSBT and NSBT.

Table 3 – Comparison between NSBT and TSBT

Product Comparison	NSBT	TSBT
Features	Modular design	No ventilation, fixed bottle design

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Functionality	Minimal human intervention	Major human intervention
Materials	Poly lactic acid	Reuse plastic bottle
Cost	RM150	RM15
Biodegradability	Yes	No
Usage duration	Recyclability for 2 years	Single-use (3 months)

The NSBT integrates advanced functionalities designed to minimise human intervention, making it highly suitable for long-term management and automation in smart farming [14]. Beyond technological advancement, NSBT prioritizes the well-being of beekeepers by addressing key ergonomic and occupational challenges, such as reducing strenuous activity, minimizing harmful postures during manual inspections and limiting prolonged sun exposure. This dual focus on innovation and human-centered design aligns with findings by [17], which highlights a growing societal emphasis on occupational safety and health within the beekeeping industry.

However, this improvement comes at a significantly higher upfront cost, RM150, ten times higher than TSBT, which only costs RM15. The higher cost may limit its adoption at grassroots. Government agencies could support by offering matching grant or subsidies. Over time, economies of scale and local manufacturing could also reduce production costs, making the solution more accessible to smallholders.

4. Conclusions

The development of the NSBT represents a significant advancement in smart farming practices by addressing critical issues contributing to CCD. Integrating user-driven design, biodegradable 3d printing materials, and real-time environmental monitoring through IoT, the NSBT offers a sustainable and technologically enhanced approach to stingless beekeeping. With stable internal environmental conditions observed and a business model tailored to small-scale beekeepers, the NSBT holds strong commercialisation potential. Furthermore, its alignment with SDG 2 and SDG 13 highlights its contribution to both agricultural productivity and environmental resilience.

Future studies could address NSBT performance extensively across diverse climatic regions and ecological conditions to validate its durability and adaptability.

Acknowledgement

The authors are grateful to IIUM for providing the facilities to conduct this study.

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