The System of Remote Monitoring of Microclimate Parameters of Bee Colonies

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ABSTRACT

Accurate and timely measures to preserve the native populations of the wild honey bees need a study on the influence of housing conditions and environmental factors on the quality, productivity and viability of bee colonies. The authors have developed a system for remote monitoring of microclimate parameters of wild bee colonies based on the latest LoRaWAN technology. For studying the monitoring system based on the selected data transmission technology, data collection and transmission devices are implemented in two variants – based on ready-made monoblock devices (Variant 1) and composite devices (Variant 2) based on the Atmega328P microcontroller and photovoltaic power supply system with digital temperature and humidity sensors. Field tests of an experimental remote monitoring system were carried out in actual working conditions without power supply and communication systems. The tests involved 15 monoblock ready-made RAK7204 devices (Variant 1) and nine composite devices (Variant 2) based on the Atmega328P microcontroller. After the tests, Variant 1 was excluded from further use in research due to mass failure. Variant 2 passed the tests and participated in further research. The parameters of the power supply system of measuring devices and gateways are analyzed. The results of year-round monitoring of microclimate parameters of bee colonies were obtained. The study results prove the efficiency of the monitoring system based on LoRaWAN technology with the Atmega328P microcontroller devices and its operation comfort. During the study, it was recorded that the outer air temperature dropped to –36 °C. During the same period, the internal temperature significantly exceeded the air temperature. Besides, the highest temperature in wild hives during the winter months reaches +15 °C and +35.5 °C in the summer months. The temperature difference recorded in winter between the air inside wild hives and outer air reaches Δ30 °C.

Keywords: digitalization, honey, Internet of things, LoRaWAN, microclimate, monitoring, wild beekeeping.

INTRODUCTION

Information is the most valuable resource in the modern world. Concepts like "Internet of Things", "Big Data", "Blockchain" get to the spheres of the national economy. The task of agricultural specialists is to master new information technologies and introduce them into the daily life of cultivated plants and animals effectively and safely. Thus, the propose of the paper of Nigussie et al. (2020) an IoT-based irrigation management system based on the results of a study of the problems of irrigated agricultural lands of three countries: Sub-Saharan Africa, Ethiopia, Kenya and South Africa as case studies. A resource-efficient IoT architecture that monitors soil, microclimate and water parameters and performs appropriate irrigation management is proposed.

The paper of Neethirajan et al. (2017) focuses on new technological advances in livestock health monitoring to obtain detailed and accurate information about animals' productivity, physiology and well-being. Biosensors are said to contribute to the fourth agricultural revolution by incorporating innovative technologies into cost-effective diagnostic methods that can mitigate the potentially catastrophic consequences of infectious outbreaks among farm animals.

The more natural the conditions of keeping animals, the more environmentally friendly the products. Thus, information about the environment and microclimate is essential. The wild bees honey is considered the most useful and environmentally friendly (Khisamov et al., 2019). However, its production can be complex since it is connected with natural and meteorological conditions. In the mountain forest zone of the Republic of Bashkortostan, wild beekeeping is one of the leading traditional crafts of the local population.

Burziansk wild bees (APIs mellifera mellifera) is a population of dark forest bees (Central Russian) living in the forests of the mountain forest zone of the Republic of Bashkortostan. Wild bees are listed in the Red Data Book of the Republic of Bashkortostan and the Cheliabinsk region. They are also recommended to be listed in the Red Data Book of Russia. In the Trans-Urals area of Bashkortostan, the temperature often drops to –40 °C in winter. But wild bees are resistant to low temperatures and can safely winter in hollows. Natural selection for many centuries has made them resistant to diseases.

The revival and preservation of wild beekeeping are of economic, ecological, cultural and national importance. Scientists of the Bashkir State Agrarian University set out to study the influence of housing conditions and environmental factors on the quality, productivity and viability of bee colonies to preserve the native populations of the wild honey bees.

Paper of Zacepins et al. (2015) analyzes existing studies and notes that the most popular methods of monitoring the level of colonies are temperature, humidity, weight, sound, vibration and video surveillance monitoring. There are many solutions available on the market. Beekeepers should individually choose a suitable solution depending on the financial aspects and the infrastructure of the apiary location. Authors note that temperature monitoring seems to be developing towards wireless technologies and alternative energy sources, such as solar energy. These systems should be easy to use, maintain and provide remote access to data. Another paper of Kviesis and Zacepins (2015) considers various architectures of automatic monitoring systems for monitoring the hive temperature in real-time, identifying their advantages and disadvantages. The work aims to simplify beekeepers' choice of suitable architecture and proposes a selection algorithm.

Study of Zacepins et al. (2016) proposes a method for remote identification of swarming bee colonies by single-point temperature monitoring since this factor can significantly reduce profitability. Paper authors note that sound monitoring used to detect swarming has not been popular in practical beekeeping due to complex measurements, data processing and necessary decision-making procedures. The authors link the advantages of continuous temperature measurements with an increase in temperature by 1.5–3.4 °C due to the bees' flight muscles warming about 10 minutes before the swarm takes. The paper proposed to use the temperature increase based on the bees muscles warming as a swarming indicator remotely and automatically if the temperature increase before takeoff can be detected, and the decision-making algorithm can recognize swarming.

Paper of Debauche et al. (2018) proposes a technical solution providing researchers with a platform for better understanding and measuring the impact factors that lead to the mass bees extinction. The proposed model is also a digital and valuable tool for beekeepers to monitor their hives better. Using this model, beekeepers can regularly inspect their hives to check the colony health.

Brazilian scientists used daily thermal diagrams to develop a mechanism for determining the temperature increase inside the hive (microclimate) (Kridi et al., 2016). The paper presents results showing different temperature regimes associated with the hive conditions. Temperature is identified as a critical factor for potential escaping conditions. Bees may leave the brood nest when natural temperature regulation is not achieved due to overheating and heat stress. In this context, the authors propose proactive monitoring of hives using a wireless sensor network that detects atypical heating.

Paper of Henry et al. (2019) proposes a system of wireless sensors for online monitoring of the hive microclimate parameters, including temperature, relative humidity and sound. Wi-Fi radio waves prove not to affect these parameters inside the hive, unlike the wired version of the developed sensor network. Based on the results of studies from September 5 to October 8, 2015, the authors concluded that Wi-Fi radio waves do not disturb bees in hives. Studies on the presented wireless sensor network prove that the potential effect of RF-EMR can be minimized by reducing

the communication time and periodically sending data to the server with a 15-minute interval.

Braga et al. (2020) state that an accurate forecasting method allows predicting the bee colony health by homeostasis, weight, inspections and weather data. A forecasting model based on a random forest algorithm with a hit rate of more than 90 helps a beekeeper avoid losses of winter colonies and to prevent bee problems. The beehives used in this study belong to the Bayer Bee Care Center (BBCC) and are in Indiana, North Carolina, Pennsylvania, and Utah, the USA.

Currently, there are many studies of the beehives parameters, technical proposals for monitoring and automation of microclimate management of hives and winter apiary houses. However, the proposed monitoring systems are designed for apiarian beehives. They are built using transmission devices based on wired or GSM transmitters, transmitting large amounts of information but requiring significant energy and material costs. Besides, the beekeeping conditions in apiarian hives and wild hives are significantly different. Wild hives are traditionally located on trees in the forest all year round in natural conditions, even in winter at subzero temperatures.

Scientists of the Republic of Bashkortostan, the Russian Federation, consider in the paper of Khisamov et al. (2019) the nectarine potential and cadastral assessment of the honey-bearing resources of the Altyn Solok reserve, created for the conservation and reproduction of the Burzian bee population Apis Mellifera Mellifera L.

Sultanova eet al. (2019) raise the question of the influence of certain agro-climatic factors on the nectar productivity of wild and cultivated plants. They propose an approach of combining biological, zootechnical and economic assessment of the fodder beekeeping base. The botanical assessment makes it possible to identify how rich the floristic composition of honey plants is and how high the nectar productivity of a particular area, considering that the Republic of Bashkortostan includes three natural zones – forest-steppe, steppe and mountain forest. However, these papers do not offer technical solutions to study the bee colonies microclimate in the specified area of honey cultivation.

The same article presents the results of the implementation and testing of devices for remote monitoring of the wild bee colonies microclimate parameters in real-time with wireless transmission of information via one-way radio communication based on LoRaWAN technology. The technical solution is being developed for year-round use in the forests of the mountain forest zone of the Trans-Urals region of the Republic of Bashkortostan. The paper aims to develop and investigate a remote monitoring system of the wild bee colonies microclimate parameters in real-time in conditions of limited energy and communication access. Tasks:

1. Analysis of existing systems for remote monitoring of microclimate parameters of wild bee colonies in the absence of power supply and communication systems.
2. Development of a system for remote monitoring of microclimate parameters of wild bee colonies.
3. Field-testing of an experimental system for remote monitoring of microclimate parameters of wild bee colonies in the absence of power supply and communication systems.
4. Year-round monitoring of microclimate parameters of wild bee colonies.

MATERIALS AND METHODS

The proposed system is designed to measure the temperature and relative humidity of the air in the hives and the outer atmospheric air in the area. The monitoring system is based on the latest LoRaWAN technology of one-way information transmission via radio waves in a free frequency range. The distance range of stable relations is up to 15 km along the line of sight. As for power consumption, one device can operate for up to 10 years on a 3400 mAh battery. One gateway can serve up to 5 thousand terminal nodes per square kilometre (km²) (Valishin et al., 2020a, 2020b). The data transmission rate is 5 min and more.

For studying the monitoring system based on the selected data transmission technology, data collection and transmission devices are implemented in two variants – based on ready-made RAK7204 monoblock devices (variant 1) and composite devices (variant 2). The RAK7204 device (variant 1) is a monoblock device of 90×85×34 mm with a replaceable lithium battery with a capacity of 3500 mAh and a claimed service life of more than two years. Parameters:
- operating temperature: –40 °C to +85 °C;
- temperature measurement range: –40 °C to + 85 °C;
- gas pressure measurement range: 30–300 kPa;

- indoor air quality range: 0–500;
- power supply battery temperature range: –55 °C to 85 °C (Rak, 2021).

Composite devices (variant 2) are based on the Atmega328P microcontroller. Figure 1 shows the block diagram of the system with the variant two devices. It includes the following main nodes: a device for measuring and transmitting parameters; a device (gateway) for receiving and transmitting information to the server; an energy source, i.e., a solar power plant with a Delta SM 50–12P photovoltaic panel, a DELTA GEL 12–26 helium battery and a Delta PWM 2410 L charge controller. The device has digital temperature sensors DS18B20-IP67–2 and humidity sensors sht20. The battery accumulator capacity is high to provide power supply in winter at subzero temperatures (up to –40 °C).

Two wild beehives, one bee butt and three wintering hives were used for research conducted in the Shulgan-Tash State Natural Biosphere Reserve of the Burziansky district of the Republic of Bashkortostan.

After trial tests of the operability of the devices, the use of Variant 1 devices in the study was suspended. Therefore, only Variant 2 devices were used to monitor the parameters in wild hives and the bee butt. Figure 2 shows the layout of temperature (t1–t6) and humidity (φ) sensors compiled by the authors based on the traditional scheme of the wild hive structure.

According to long-standing traditional technologies, the wild hives and the bee butt used in the study were manufactured and placed on forest trees. The wild hives are caved in living or dead standing isolated trees. The bee butt is a wild hive analogue and is caved in a felled tree trunk. The study used wild hives and a bee butt made of pine wood. The monitoring system and all sensors were installed in the autumn at an atmospheric temperature from 0 to –10 °C. At such a temperature, bees are not very active. Thus, sensors were placed inside the wild hive through the beehive entrance.

Figures 3 and 4 show the placement of sensors, information transmission devices and the power supply system. Temperature sensors are also placed in drilled blind holes with 50 and 150 mm depth to study the thermal conductivity of the wild hive wood wall. The holes are closed with insulation material to preserve the thermal insulation properties of the drilled parts of the wood wall (Figures 3 and 4).

RESULTS AND DISCUSSION

Before installation, both device variants were tested under the same working conditions. They were installed in apiary houses (winter hives) and outdoors under a waterproof canopy with the following air parameters: temperature from –35 °C to +35 °C, relative humidity 20–100%, atmospheric pressure 95–102 kPa. Three apiary
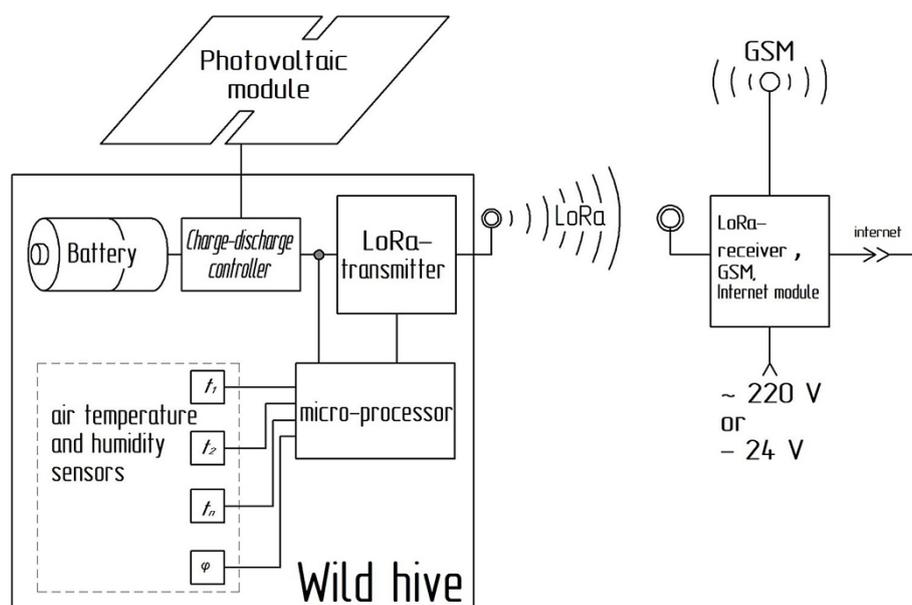

Figure 1. Structure of the microclimate monitoring system for wild bee colonies (author's development)
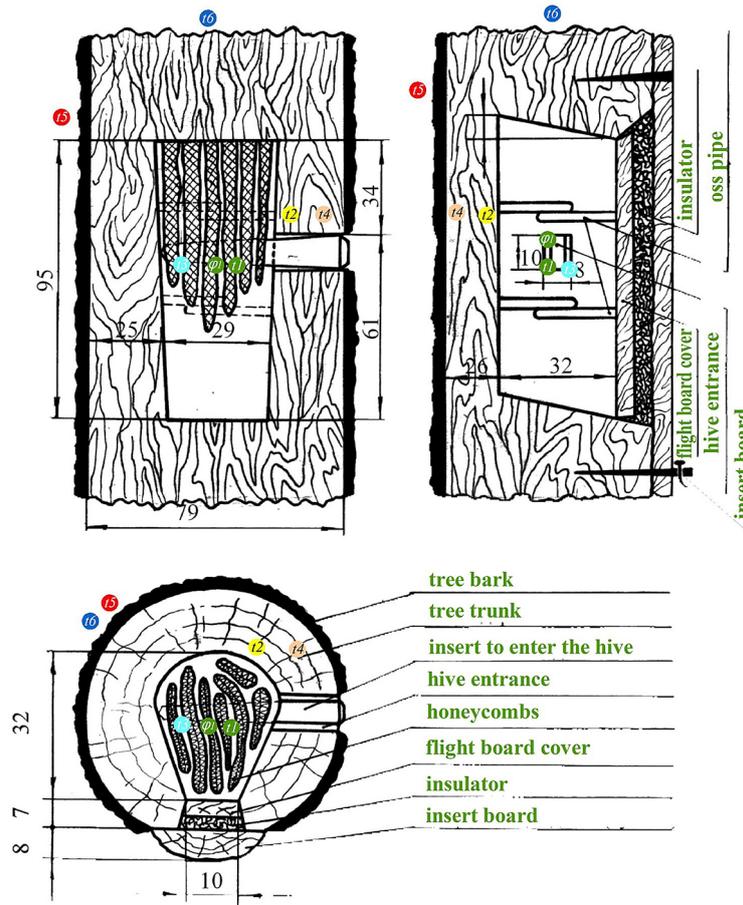
Figure 2. Layout of temperature and humidity sensors in the wild hive (author's development) (bee butt No. 1)

houses participated in the tests in the Shulgan-Tash Nature Reserve of the Burziansky district of

Figure 3. Installation of temperature and humidity sensors to the wild hive: 1 – beehive entrance; 2 – sensor wires; 3 – thermal insulation coating of sensors in the walls of the wild hive (t2, t4) (author's development)

the Republic of Bashkortostan. The results of the device operability tests are presented in Table 1.

Further use of monoblock devices (variant 1) in the study was suspended due to their massive failure. A manual reboot was possible. However, the devices failed 1–2 days after restarting. Trial tests of the proposed system using Variant 1 and Variant 2 devices showed the degree of their operability in extreme natural conditions of a given area. 100% of Variant 1 devices failed less than a month after testing. The reason for the failures has not been definitively identified. The most probable reasons are:

1. Oxidation and electrical locking of conductive parts due to water condensate owing to huge temperature and humidity swings characteristic of the mountain forest zone climate of the republic of bashkortostan;
2. Disconnection from the main lorawan gateway due to a software error.

The composite devices of variant 2 turned out to be more reliable. The operating time to failure was 122 days.

Figure 4. Power supply system of the measurement and transmission device (variant 2): 1 – measurement and transmission device; 2 – battery; 3 – charge-discharge controller; 4 – photovoltaic panel (author's development)

To evaluate the system energy consumption, the results of monitoring the energy source parameters need consideration. The energy source, in this case, is a solar power plant with helium batteries. Table 2 summarises the parameters of energy sources, system elements, and the monitoring results during the test.

Table 2 shows that the energy consumed by the measurement and data transmission device (Variant 2) in standby mode is less than 2 µA. The rate of battery voltage reduction is not significant and corresponds to the self-discharge rate, taking into account the low ambient temperature. The LoRaWAN gateway and GSM modem consume much more energy (6–7 Watts), and the battery

voltage decreases sharply in the absence of energy from the solar panel.

LoRaWAN technology uses a frequency range that is currently free on the territory of the Russian Federation. Developers offer platforms with a custom interface cloud system. The paper authors selected one of such platforms called "Grafana", where the measurement results are stored in the cloud and can be presented as time diagrams of temperature and humidity at various points of hives and apiary houses. Figures 5 and 6 show the microclimate parameters of the wild hive and bee butt, respectively, in the same period from 1 to December 16. The measurement results were recorded and delivered to the data collection point. The time intervals between measurements are stable. The diagrams are pretty logical and convenient for analysis. The atmospheric temperature (t_6) changes markedly with daily frequency. The temperature in the walls of the wild hives (t_2, t_3) changes similarly, but with smaller differences. During the study, it was recorded that the outer air temperature dropped to –36 °C. During the same period, the internal temperature significantly exceeded the air temperature. Besides, the highest temperature in wild hives during the winter months reaches +15 °C and +35.5 ° C in the summer months. The temperature difference recorded in winter between the air inside wild hives and outer air reaches Δ30 °C.

In addition to the main parameters, the system monitors technical device parameters such as the battery's charge level (voltage, signal level, and microcontroller temperature). The obtained monitoring results allow analyzing the relationship of the microclimate parameters in the wild hives and hives, including the activity, mass, productivity and other characteristics of bee colonies. Diagrams presented in Figures 5 and 6 prove the change in the relative humidity of the air inside wild hives and the bee butt from 85% to 97% with the change in the temperature. Therefore, a higher and more stable temperature and humidity (Figure 6)

Table 1. Operating time of measurement and data transmission devices until their failure

Type, a brand of the device	Variant 1 (RAK7204)	Variant 2 (composite device)	
Number of devices in the test, pcs	15	9	
Operating time of the first device until its failure, days	9	122	-
Operating time of the i-th device until its failure, days	26 (No.15 of 15 pieces)	-	214 (No. 2 of 9 pieces)
Degree and reason of failure	Ultimate extinction of data transmission	Humidity sensor failure	Battery charge-discharge controller failure

Table 2. Parameters of energy sources and system elements when testing the system for operability in the area conditions

		Measurement and data transmission device (Variant 2)	LoRaWAN MikroTik wAP LR8 kit gateway	MikroTik LHG LTE kit (RBLHGR&R11e-LTE)
System element	Title	Measurement and data transmission device (Variant 2)	LoRaWAN MikroTik wAP LR8 kit gateway	MikroTik LHG LTE kit (RBLHGR&R11e-LTE)
	Parameters	Temperature and humidity measurements, full compliance with LoRaWAN 1.0.2	Frequency range: 2400–2483.5 MHz / LoRa: 864–870 MHz	Frequency range: LTE FDD; LTE TDD; 3G; 2G
		standby current less than 2 µA	Claimed maximum power consumption: 7 Watts	Declared max. power consumption: 6 Watts
Test time / average ambient Temperature (min...max)		42 days / -12 °C (-30...-5 °C)	48 hours / -8 °C (-30...-5 °C)	
Energy source	Title	DELTA GEL 12–26 (+ BB-PWR-8113, DC-DC converter)	2 × DELTA GEL 12–26	
	Voltage before – after, V	12.7 – 11.4 (in the absence of the charge from solar panels)	30 – 20 (in the absence of the charge from solar panels)	

indicates that the bee colony's mass in the bee butt is more significant than in the wild hive (Figure 5). It also proves a better thermal insulation quality of the bee butt material.

A more detailed analysis reveals a relationship between bee activity and the daytime, atmospheric pressure, etc. For instance, there are temperature jumps (Figure 6) in the wild hives every winter morning, which the temperature overregulation by bees may explain.

In general, the monitoring system based on LoRaWAN technology is efficient and convenient in this research field. The results of the tests allow the authors to agree with the analysis in paper of Tao et al. (2021), which prove that "LoRaWAN technology can provide communication in large agricultural fields with low energy needs due to low data transfer rate. Unlike other wireless communication technologies such as Bluetooth, ZigBee and Wi-Fi, the advantage of LoRa technology
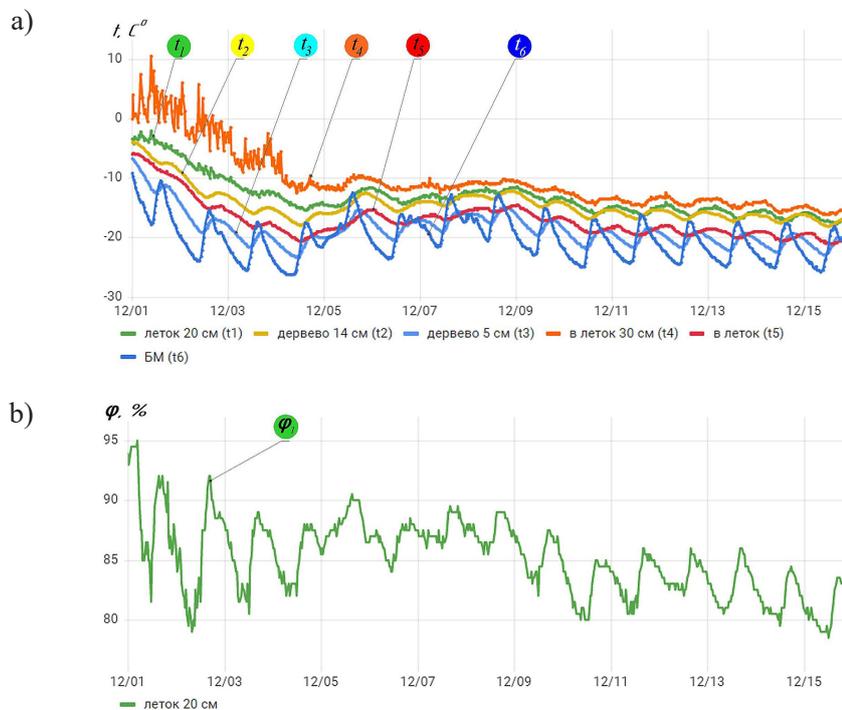

Figure 5. (a) Microclimate parameters in wild hive No. 2: t_1 – temperature in hive entrance (20 sm); t_2 – temperature in the tree (14 sm); t_3 – temperature in the tree (5 sm); t_4 – temperature in hive entrance (30 sm); t_5 – temperature in hive entrance; t_6 – temperature on microcontroller unit; (b) φ_1 – humidity in hive entrance (20 sm)
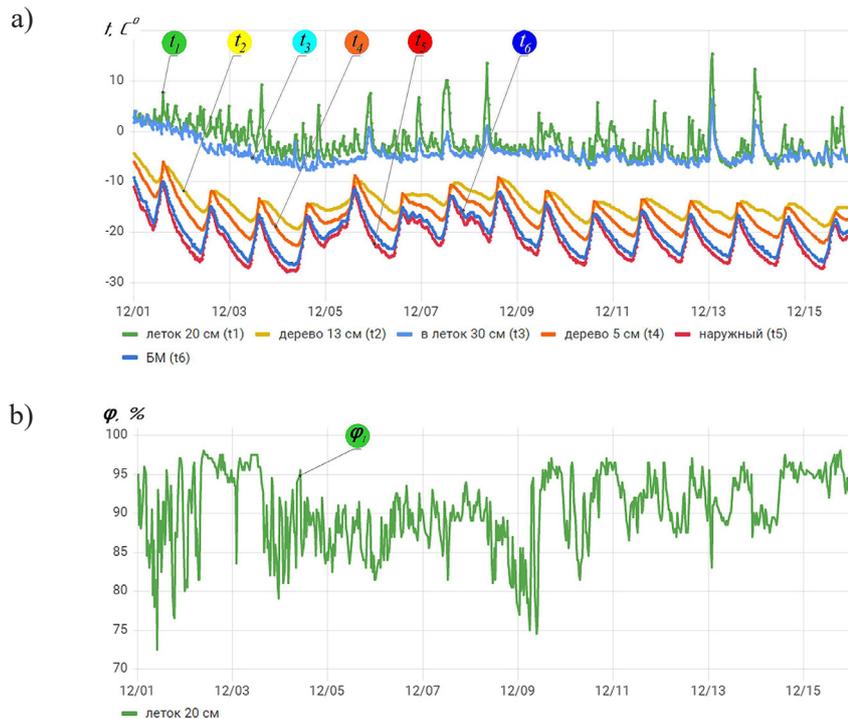
Figure 6. (a) Microclimate parameters in bee butt No. 1: t_1 – temperature in hive entrance (20 sm); t_2 – temperature in the tree (13 sm); t_3 – temperature in hive entrance (30 sm); t_4 – temperature in the tree (5 sm); t_5 – temperature in exterior; t_6 – temperature on microcontroller unit; (b) φ_1 – humidity in hive entrance (20 sm)

is low power consumption." However, it's not worth relying on the value of the communication devices range of 45 km for rural areas stated in the paper of Vuran et al. (2018). In the mountain forest zone, the communication range is significantly lower. The devices based on the accepted technology have advantages over measurement devices widely used today, including those with GSM transmitters. They require less energy and material costs. These advantages are more evident when many endpoints of measuring and data transmission devices are most densely located or placed at a distance accessible for communication with the receiving gateway.

Wild hives in traditional wild beekeeping are often distributed far from each other. In this case, on the one hand, many receiving gateways are necessary to collect information. But, on the other hand, the LoRaWAN architecture makes it possible to more economically ensure the communication of measurement devices with the server in those wild hives located in areas with a weak GSM signal. However, LoRaWAN gateways consume significantly more energy than endpoints. The results of tests of the power supply system with solar panels and batteries allow concluding that the balance of batteries and solar panels capacities is worth redistributing in favour

of gateways and modems to increase their power supply reliability. Low-power terminal devices can get power from small-sized lithium-ion batteries (LIB) with preheating charging technology proposed in papers of Guo et al. (2022) and Nambisan et al. (2021). There are also other storage devices, such as ionistors, also called supercapacitors (Savilov et al., 2015).

Composite devices (Variant 2) are based on Atmega328P, which proved to be the easiest, versatile, convenient and reliable microcontroller as noted in papers od Sánchez et al. (2015) (Atmega328) and Flores et al. (2019) (Atmega1281). The RAK7204 monoblock ready-made device has recently appeared on the market. Therefore, such a device needs more testing and changes in the required working conditions or further improvements. There is no scientific information about this device.

The Grafana platform has also proven to be a simple and convenient tool for visualization and monitoring results analysis. Papers of Cicioğlu and Çalhan (2021) and Venkatramulu et al. (2021) propose to use Grafana as an open-source visualization and query processing platform for data scientists and researchers.

The obtained monitoring results show that the outer air temperature dropped to –36 °C

during the study, whereas papers of Braga et al. (2021), Edwards-Murphy et al. (2016), Flores et al. (2019), and Sánchez et al. (2015), present studies on temperatures above +5 °C. The results of monitoring in winter show periodic daily temperature jumps in the wild hives, which temperature overregulation by bees may explain. Unlike hot periods when cooling inside the hive is carried out by dispersing and weathering excess heat and moisture, bees form a club to maintain proper temperature in winter. The bee movement inside the club and the gradual change of the outer bee layer with the bee core of the club regulate the temperature in winter. The bee club can gradually move inside the wild hive as bees consume honey. Thus, the air temperature recorded by the sensors in the wild hive and the actual temperature of the bees can vary significantly. For instance, Figure 5 shows the temperature decrease to –15 °C inside the wild hive. This phenomenon explains the negative temperatures predominance inside the wild hive during the cold winter period. However, the ability of the colony to survive the cold depends on maintaining a constant temperature of about 35°C in the central zone of the brood colony (Braga et al., 2020). The same paper also gives the results proving that the internal temperature in hives in winter ranges from 3 °C to +10 °C in fewer sound conditions and from –10 °C to +15 °C in more sound conditions.

REFERENCES

1. Braga A.R., Freitas B.M., Gomes D.G., Bezerra A.D., Cazier J.A. 2021. Forecasting sudden drops of temperature in pre-overwintering honeybee colonies. Biosyst. Eng., 209, 315–321.

2. Braga A.R., Gomes D.G., Rogers R., Hassler E.E., Freitas B.M., Cazier J.A. 2020. A method for mining combined data from in-hive sensors, weather and apiary inspections to forecast the health status of honey bee colonies. Comput. Electron. Agric., 169, 105161.

3. Cicioğlu M., Çalhan A. 2021. Smart agriculture with internet of things in cornfields. Comput. Electr. Eng., 90, 106982.

4. Debauche O., El Moulat M., Mahmoudi S., Boukraa S., Manneback P., Lebeau F. 2018. Web monitoring of bee health for researchers and beekeepers based on the internet of things. Procedia Comput. Sci., 130, 991–998.

5. Edwards-Murphy F., Magno M., Whelan P.M., O'Halloran J., Popovici E.M. 2016. b+ WSN: Smart beehive with preliminary decision tree analysis for agriculture and honey bee health monitoring. Comput. Electron. Agric.. 124, 211–219.

6. Flores J.M., Gil-Lebrero S., Gámiz V., Rodríguez M.I., Ortiz M.A., Quiles F.J. 2019. Effect of the climate change on honey bee colonies in a temperate Mediterranean zone assessed through remote hive weight monitoring system in conjunction with exhaustive colonies assessment. Sci. Total Environ., 653, 1111–1119.

7. Guo S., Yang R., Shen W., Liu Y., Guo S. 2022. DC-AC hybrid rapid heating method for lithium-ion batteries at high state of charge operated from low temperatures. Energy, 238, 121809.

8. Henry E., Adamchuk V., Stanhope T., Buddle C., Rindlaub N. 2019. Precision apiculture: Development of a wireless sensor network for honeybee hives. Comput. Electron. Agric., 156, 138–144.

9. Khisamov R., Yanbaev Y., Yumaguzhin F., Farkhutdinov R., Ishbulatov M., Onuchin M., Mustafi R., Rakhmatullin Z., Talipov E. 2019. Nectariferous potential and cadastral evaluation of honey resources of the wildlife Altyin Solok Reserve created for the conservation and reproduction of the Burzian population of the Apis Mellifera Mellifera L. Bulg. J. Agric. Sci., 25(2), 140–149.

10. Kridi D.S., de Carvalho C.G.N., Gomes D.G. 2016. Application of wireless sensor networks for beehive monitoring and in-hive thermal patterns detection. Comput. Electron. Agric., 127, 221–235.

11. Kviesis A., Zacepins A. 2015. System architectures for real-time bee colony temperature monitoring. Procedia Comput. Sci., 43, 86–94.

12. Nambisan P., Saha P., Khanra M. 2021. Real-time optimal fast charging of Li-ion batteries with varying temperature and charging behaviour constraints. J. Energy Storage, 41, 102918.

13. Neethirajan S., Tuteja S.K., Huang S.T., Kelton D. 2017. Recent advancement in biosensors technology for animal and livestock health management. Biosens. Bioelectron., 98, 398–407.

14. Nigussie E., Olwal T., Musumba G., Tegegne T., Lemma A., Mekuria F. 2020. IoT-based irrigation management for smallholder farmers in rural sub-Saharan Africa. Procedia Comput. Sci., 177, 86–93.

15. Rak. 2021. IoT Made Easy. https://store.rakwireless.com

16. Sánchez V., Gil S., Flores J.M., Quiles F.J., Ortiz M.A., Luna J.J. 2015. Implementation of an electronic system to monitor the thermoregulatory capacity of honeybee colonies in hives with open-screened bottom boards. Comput. Electron. Agric. 119, 209–216.

17. Savilov S.V., Strokova N.E., Ivanov A.S., Arkhipova E.A., Desyatov A.V., Hui X., Aldoshin S.M., Lunin V.V. 2015. Nanoscale carbon materials from

hydrocarbons pyrolysis: Structure, chemical behavior, utilisation for non-aqueous supercapacitors. Mater. Res. Bull., 69, 13–19.

18. Sultanova R.R., Gabitov I.I., Yanbaev Y.A., Yumaguzhin F.G., Martynova M.V., Chudov I.V., Tuktarov V.R. 2019. Forest melliferous resources as a sustainable development factor of beekeeping. Isr. J. Ecol. Evol., 65(3–4), 77–84.

19. Tao W., Zhao L., Wang G., Liang R. 2021. Review of the internet of things communication technologies in smart agriculture and challenges. Comput. Electron. Agric., 189, 106352.

20. Valishin D.E., Leontiev D.S., Muhortova E.I. 2020. Prospects for applying LoRaWAN communication technology in portable weather stations for agriculture. In: The current state, traditions and innovative technologies in the development of agriculture: proceedings of the International Scientific and Practical Conference. LLC "BGC", Ufa, 16–21.

21. Valishin D.E., Mukhortova E.I., Shavaliev I.F. 2020. Comparative analysis and directions of improvement of portable weather stations for agriculture.

In: Actual problems of energy supply of enterprises: materials of the IV All-Russian Scientific and Practical Conference within the framework of the Russian Energy Forum and the XXV Anniversary International Exhibition "Energy of the Urals". Bashkir Exhibition Company LLC, Ufa, 10–15.

22. Venkatramulu S., Phridviraj M.S.B., Srinivas C., Rao V.C.S., 2021. Implementation of Grafana as open source visualization and query processing platform for data scientists and researchers. Mater. Today in press.

23. Vuran M.C., Salam A., Wong R., Irmak S. 2018. Internet of underground things in precision agriculture: Architecture and technology aspects. Ad Hoc Netw., 81, 160–173.

24. Zacepins A., Brusbardis V., Meitalovs J., Stalidzans E. 2015. Challenges in the development of Precision Beekeeping. Biosyst. Eng., 130, 60–71.

25. Zacepins A., Kviesis A., Stalidzans E., Liepniece M., Meitalovs J. 2016. Remote detection of the swarming of honey bee colonies by single-point temperature monitoring. Biosyst. Eng., 148, 76–80.