Review Article

ENHANCING AGRICULTURE THROUGH WIRELESS SENSOR NETWORKS

ABSTRACT

Solar-powered wireless sensor networks (WSNs) play a crucial role in modern agriculture, enhancing crop yield and quality while reducing labor requirements. By employing sensors and communication technologies like ZigBee and Bluetooth, these networks collect real-time data on various environmental parameters, facilitating remote monitoring and prompt action by farmers. Leveraging solar energy through photovoltaic (PV) systems, these WSNs ensure sustained power supply, enabling autonomous operation even in remote areas. Recent studies highlight the effectiveness of solar-powered WSNs in diverse agricultural applications such as automated irrigation, soil sensing, and weather monitoring. Integration of PV technology with WSNs offers simplicity in installation and long-term energy sustainability, making them an attractive choice for farmers seeking efficient and self-sustained agricultural practices.

Keywords: *Crop yield enhancement, Long-term sustainability, Photovoltaic systems, Remote monitoring, Solar-powered WSNs.*

1. INTRODUCTION

Solar-powered wireless sensor networks (WSNs) revolutionize agriculture by integrating advanced technology into traditional farming. Precision agriculture (PA) combines agriculture with information technology to boost crop yield while minimizing labor. Sensors collect real-time data on crucial parameters like temperature and soil moisture, transmitted via WSNs for remote monitoring. IoT enhances efficiency with low-cost connectivity, enabling applications like livestock monitoring and automated irrigation (Rahul *et al*., 2018). Energy harvesting, particularly solar power, addresses WSNs' battery limitations, ensuring sustainability. Solar-powered WSNs offer clean, extended energy solutions, transforming agricultural practices.

In this context, this paper delves into the significance and applications of solar-powered WSNs in agriculture, highlighting recent advancements, energy harvesting techniques, and real-world implementations. Through an in-depth exploration, we aim to underscore the transformative potential of solar-powered WSNs in driving agricultural innovation and sustainability.

2. MATERIALS AND METHODS

Utilizing solar power in agricultural wireless sensor networks (WSNs) involves integrating photovoltaic (PV) technology with sensor nodes. Various studies demonstrate its effectiveness in applications such as automated irrigation, soil sensing, and weather monitoring, highlighting its simplicity in setup and long-term sustainability.

2.1 Leveraging Solar Power for Agricultural Wireless Sensor Networks

The concept of Precision Agriculture (PA) combines agriculture with information technology to enhance crop yield and quality. Crop yield monitoring, at 61.4%, is the predominant PA technique (Vuran *et al*., 2018). Various technologies like ICT, sensors, information processing, and GIS are utilized to boost profitability and reduce labor in agricultural practices (Feng *et al*., 2019). Sensors integrated into agriculture enable real-time data collection of vital parameters like temperature, soil moisture, and atmospheric conditions. This data, collected via a wireless sensor network (WSN), can be analyzed for informed decision-making. Farmers can remotely monitor crops and equipment using computers or smartphones, facilitating prompt action (Abdu and Salamah, 2011 and Thakur *et al*., 2019). WSN, the second-largest network globally, enhances efficiency and sets the groundwork for broader Internet of Things (IoT) adoption in agriculture (Abo-Zahhad *et al*., 2015 and Syafarinda *et al*., 2018).

2.2 Wireless sensor network (WSN)

A wireless sensor network (WSN) comprises sensor nodes (motes) forming an ad-hoc network to sense, measure, and gather environmental data. Each node consists of a power unit, sensing unit, computing unit, and communication unit (Akbari, 2014, Kumar and Ilango 2018 and Thakur *et al*., 2019). Nodes detect real-time ecological phenomena, converting them to digital signals for processing and storage in the computing unit. Processed data is then shared via the communication unit with other nodes or end users. Nodes can communicate with a server/base station in centralized or decentralized architectures, employing various topologies like mesh or star. The schematic diagram of a typical WSN and its components is shown in Fig. 1. As depicted in the illustration, a Wireless Sensor Network (WSN) typically comprises numerous sensor nodes and a gateway node. Key attributes of WSNs include their ease of application, capacity for scalability to vast scales, node mobility, and robustness. These networks excel in capturing data from physical phenomena rather than relying on individual sensors. Consequently, the malfunction of a single node will not significantly impact the entire network (Akhtar and Rehmani, 2015 and Kiani and Seyyedabbasi, 2018).

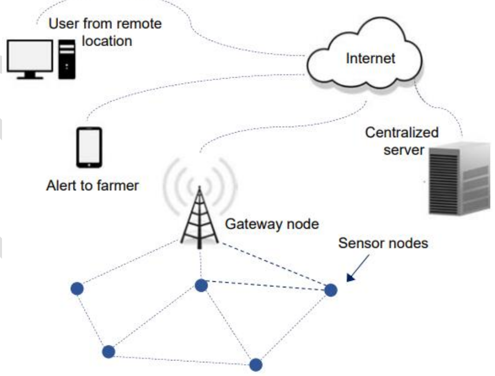

Figure.1: The general Architecture of a WSN. *Source*: Kumar and Ilango, 2018 and Thakur *et al*., 2019.

In agricultural contexts, Wireless Sensor Networks (WSNs) are typically categorized into two primary types: terrestrial and subterranean. Terrestrial WSNs (TWSNs) involve deploying sensor nodes above the ground to assess land conditions. Subterranean WSNs (UWSNs) employ sensor nodes placed within the soil of agricultural fields for real-time sensing and monitoring of soil conditions (Bader *et al*., 2014 and Kiani and Seyyedabbasi, 2018). Different technologies within Wireless Sensor Networks (WSNs) facilitate efficient data communication based on their application, power consumption, band frequency, distance, and data rate. These technologies include ZigBee, Bluetooth, Wibree, WiFi, GPRS, and WiMAX (Table 1).

Table 1: Different available communication technologies for WSN$_s$. Source: (Thakur *et al*., 2019)

Specifications			**Technologies**		
	Zigbee	**Bluetooth**	**Wi-Fi**	**GPRS 2G/ 3G/4G**	**WiMax**
Standard	IEEE 802.15.4	IEEE 802.15.1	IEEE 802.11a, d,g,n	-	IEEE 802.16. A,e
Frequency band	2.4 GHz	2.4 GHz	2.4 GHz	2.4 GHz	2.4 GHz
Range	10-100 m	100 m	32 m	Coverage area of GSM	30moles
Data rate	20 Kbit/s to 250 Kbit/s	1 Mbps	11-54 mbps	5-100 kbps/ 200 kbps/ 0.1-1 GB	50-100 Mbps
Power consumption	Low	Medium	High	Medium	Medium
Cost	Low	Low	High	Medium	High
Modulation/protocol	DSSS, CSMA/ CA	FHSS, GFSK	DSSS/ CCK, OFDM	SNDCP, LLC	OFDM
Security	128 bits	64 or 128 bits	128 bits	128 bits	160 bits

2.3 Internet of things (IoT)

The Internet of Things (IoT) encompasses a network of inexpensive, energy-efficient physical objects equipped with embedded electronics, sensors, and connectivity, facilitating data exchange. Processed data is sent to cloud computing via a gateway for storage and decision-making (Fig. 2) (Wark *et al*., 2007, Na and Isaac, 2016 and Heble *et al*., 2018). The main goals of using IoT networks in agriculture are improving efficiency as well as increasing accuracy and profitability.

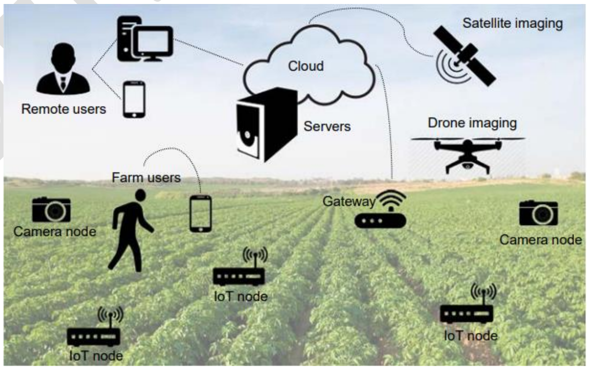

Figure 2: Schematic view of IoT deployment in the field.

Key agricultural applications of IoT systems include livestock monitoring, automated irrigation, soil sensing, and weather monitoring (Ojha, 2015, Navulur *et al*., 2017 and Varun *et al*., 2018). For instance, IoT sensors gather ambient and soil moisture data for automated irrigation, preventing crop over- and underwatering.

Additionally, IoT-based livestock monitoring ensures proper care and feeding of animals (Dataflair, 2019). Communication technologies in IoT, along with their frequencies and coverage distances, are detailed in Table 2, with further information about these communication technologies available in Ref. (Khanna and Kaur, 2019).

Table 2: Different available communication technologies for IoT. *Source*: Khanna and Kaur, 2019.

Technology	Standard	Downlink/ uplink	Range (m)	Operating frequency (MHz)	Year of discovery
RFID[a]	Wireless	100 kbps	2	0.125-5876	1973
IEEE 802.15.4	6loWPAN	250 kbps	30	826 and 915	2003
Z-Wave[b]	Wireless	100 kbit/s	30	868.42 and 908.42	2013
LTE[c]	3GPP, LTE, and 4G	100 Mbps	35	400-1900	1991
LoRa[d]	Wireless	0.3 37.5 (kb/s)	3000-5000	169, 433, and 868 (Europe) and 915 (North America)	2012
NFC[e]	ISO 18092	106, 212, or 424 Kbits	>0.2	13.56	2004
UBW[f]	IEEE 802.15.3	11-55 Mbps	10-30	2400	2002
M2M[g]	Open to All Communication	50-150 Mbps	5-20	1-20	1973
6loWPAN[h]	Wireless	250 Kbps	30	915	2006

[a] Radio-frequency identification.
[b] Zensys wave.
[c] Long-term evolution.
[d] Longrange.
[e] Near field communication.
[f] Ultrawide band.
[g] Machine to machine.
[h] IPv6 low-power wireless personal area network.

2.4 Methods of Energy Harvesting for Wireless Sensor Networks

A primary limitation of Wireless Sensor Networks (WSNs) is the finite battery capacity of sensor nodes. Various techniques have been developed to tackle this issue, focusing on energy-efficient schemes and energy-harvesting methods. Energy harvesting techniques enable sensor nodes to harness diverse energy sources such as solar, mechanical vibration, and wind energy, converting them directly into electricity (Fig.3). The harvested energy can be stored in batteries for later use. For instance, solar energy can charge sensor node batteries during the day for night time operation. Additionally, nodes can enter low-power sleep modes to conserve energy when battery levels are low (Jawad *et al*., 2017 and Pooja *et al*., 2017).

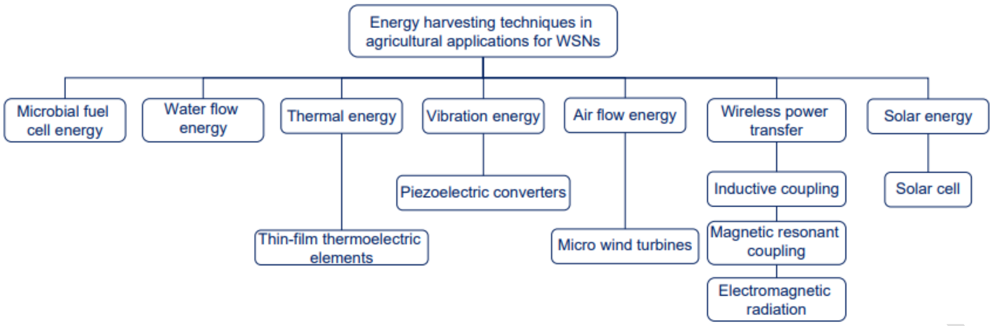

Figure 3: Energy-efficient schemes in agriculture for WSNs. *Source*:Jawad *et al*., 2017

2.5 Utilizing Solar-Powered Wireless Sensor Networks in Agricultural Settings

Solar energy, via photovoltaic (PV) technology, can be employed in agriculture using Wireless Sensor Networks (WSNs) (Jawad *et al*., 2017 and Nurzaman *et al*., 2018). Solar cells provide sustainable energy for sensor nodes, though solar energy availability varies with time and season (Pooja *et al.*, 2017). Despite limitations such as reliance on disposable lithium batteries, emerging power supply methods like supercapacitors and rechargeable batteries show promise. A typical solar PV system for WSNs comprises solar cells/modules, control circuits, and batteries, enabling extended and clean energy provision (Li and Shi, 2015, Zou et al., 2016 and Cong *et al*., 2017).

Pooja *et al.* (2017) proposed a solar-powered automated irrigation system tailored for remote regions. Comprising a solar pumping system and automatic irrigation unit, the setup employed solar panels to charge a battery for motor power, regulated by a sensing circuit (Fig.4). Soil moisture and temperature data were gathered by a sensor node network and transmitted to a remote station (Leah *et al*., 2010). The study found solar PV irrigation to be cost-effective for small, distant field applications compared to conventional energy sources.

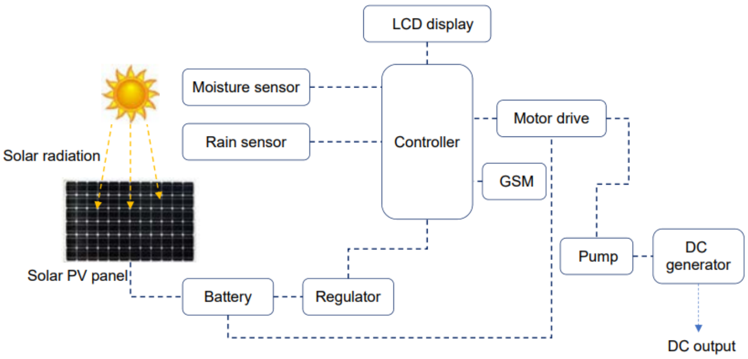

Figure 4: Block diagram of a solar-powered irrigation system based on WSNs. Source: Pooja *et al*., 2017.

Zhang *et al*. (2017) devised a wireless monitoring node employing solar PV panels with an automated tracker designed for paddy field settings. The nodes captured various field parameters such as moisture, temperature, pH, water level, and light intensity. Processed data was then transmitted to remote monitoring software via a GPRS module (Fig. 5). The incorporation of an automatic tracker enhanced solar PV panel efficiency, with the battery charged by the panel during daylight hours via a controller.

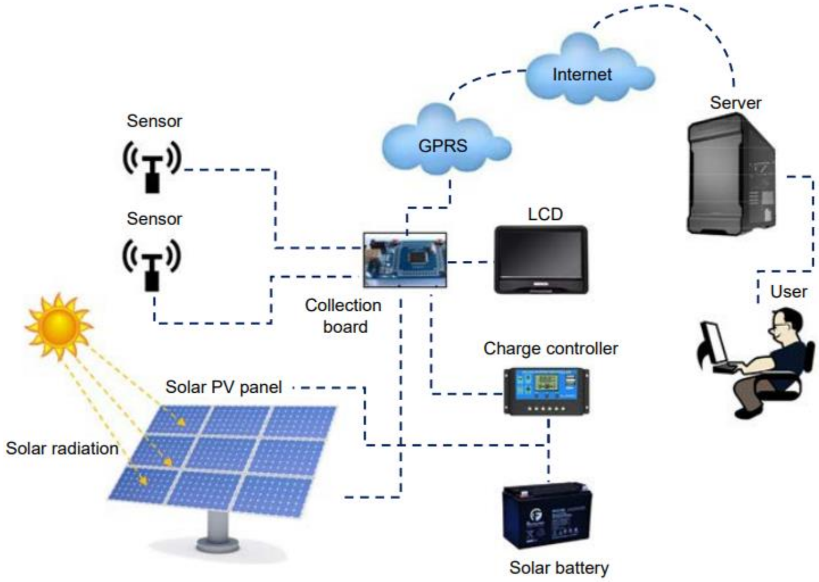

Figure 5: The overall framework for a solar-powered WSN system developed in Ref. (Bhangale and Bhide, 2019).

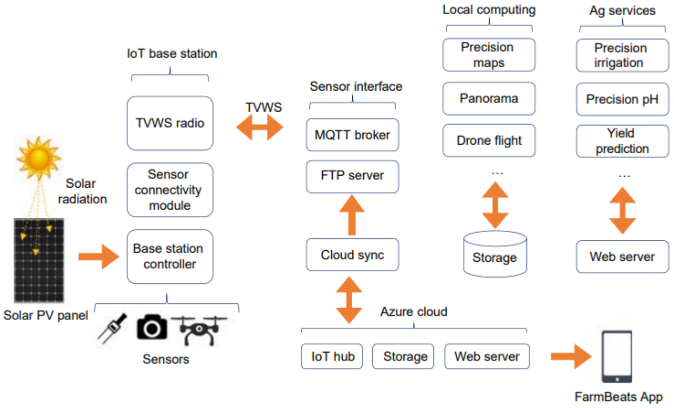

Figure 6: Schematic diagram of the FarmBeats IoT platform. *Source*:Vasisht *et al*. (2017)

The authors asserted that the proposed node could achieve accurate data transmission, leveraging solar power to meet system energy requirements. In a separate investigation by Vasisht *et al*. (2017), they introduced FarmBeats, an affordable IoT framework. This system facilitated data gathering from diverse sensors like cameras, drones, and soil sensors. Consisting of a solar-driven IoT base station and a smart gateway, it ensured cloud service accessibility (refer to Fig. 6).

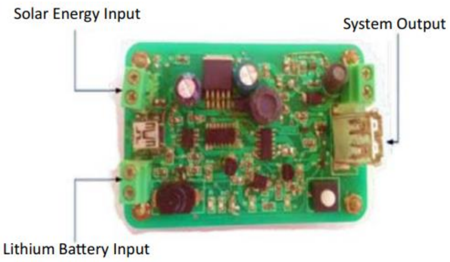

Figure 7: Circuit board of the developed solar-powered ISEH system. *Source*:Li and Shi, 2015.

Li and Shi (2015) introduced an innovative intelligent solar energy-harvesting (ISEH) system tailored for WSNs. Comprising a solar photovoltaic (PV) panel, lithium battery, and control circuit (Fig. 7), the system integrated a maximum power point tracking (MPPT) circuit to optimize PV panel efficiency. Captured solar energy could be stored in the battery, ensuring continuous operation of IoT nodes during low sunlight periods (Bhangale and Bhide, 2019). They emphasized the system's suitability for outdoor IoT sensor nodes due to its low-power nature and compatibility with energy-efficient equipment.

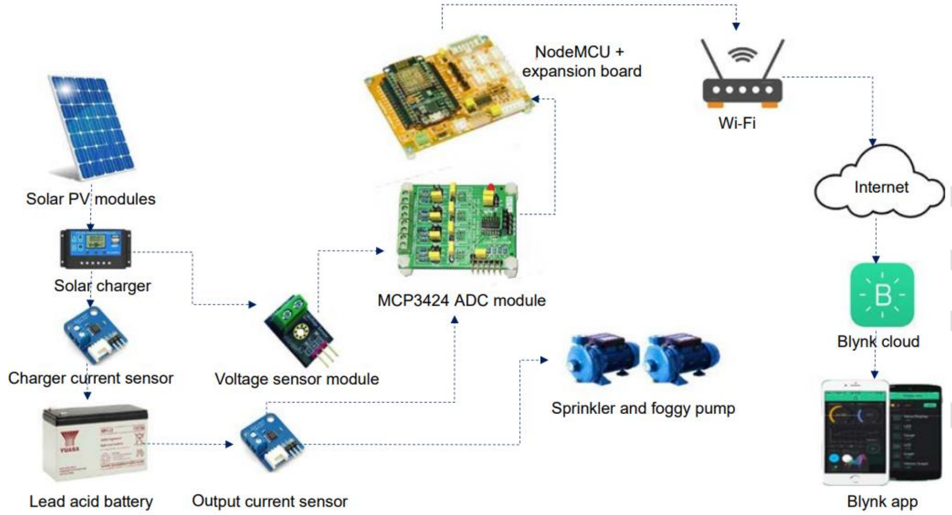

Figure 8: Concept layout of the IoT for a solar cell system with Blynk. Source:Chieochan, *et al*., 2017.

Chieochan *et al*. (2017) devised a compact off-grid solar cell system for auxiliary power in a smart-scale Lingzhi mushroom farm. Utilizing an IoT framework with voltage and current sensors, the system monitored solar cell charging voltage, battery charging current, and battery current loading for fog and sprinkler pumps as shown in Fig. 8. All solar cell data were gathered in a Blynk cloud service, facilitating real-time monitoring via a Blynk app with time-series graph visualization. The study underscored the economic viability of solar systems in remote areas devoid of grid electricity. Furthermore, the integration of IoT technology with voltage and current sensors enhanced the solar cell system's efficacy as an alternative power source for smart farming applications.

Table 3 outlines recent research on WSN applications in agriculture, employing PV technology for energy harvesting. These studies demonstrate the versatility of solar-powered WSNs in various agricultural tasks such as automated irrigation, soil sensing, and weather monitoring. Farmers favor integrating PV systems with WSNs for their straightforward setup and effective operation under adequate solar radiation. Moreover, solar PV systems offer a sustainable, long-lasting power source for sensor nodes, ensuring the network's self-sufficiency.

Table 3: PV-powered WSNs utilized in agricultural activities

Wireless “device	**Sensors/actuators**	**Application**	**Main findings**	**Reference**
GPRS/3G	Wind speed and direction, temperature, humidity, rain gauge, water, and pH levels	Weather monitoring	The battery support for sensor node operation was limited to 7 days.	Nguyen et al. (2016)

nRF24L01 IEEE 802.11b/ g/n (Wi-Fi) and cloud computing	Air temperature, wind speed and direction, leaf wetness, soil moisture, air humidity, rain volume/ fertilizers or spraying chemicals and watering system	Precision agriculture applications	The proposed system has an acceptable efficiency; • The system's structure is a little complex; • The architecture is suitable for use in a wide range of PA activities.	Khattab *et al*. (2016)
GSM module/ LoRa	Soil temperature and moisture, air temperature and humidity, and light intensity/alert messages	Automation in greenhouse	The system has been optimized for large-scale applications; • To measure environmental parameters, the module empowers the module; • Multiple parameters can be shown on a mobile application	IlieAblachim *et al.* (2016)
Wi-Fi/ GSM modem	Soil moisture, humidity, and temperature	Automated irrigation	PV power is more affordable for microirrigation systems; • PV power is cost-competitive for small, remote irrigation applications; • Precise utilization timing makes the system more efficient and low-cost.	Pooja *et al*. (2017)

3. RESULTS AND DISCUSSION

The fusion of wireless sensor networks (WSNs) and the Internet of Things (IoT) within agriculture has sparked a revolutionary transformation, markedly enhancing crop yield monitoring by 61.4% in precision agriculture (PA). Leveraging technologies like information and communications technology (ICT), sensor technology, and geographic information systems (GIS) has significantly boosted profitability and slashed labor demands in farming activities. WSNs, comprising sensor nodes with diverse components, facilitate real-time data capture and analysis, empowering remote monitoring of crops and equipment. This technology's scalability, mobility, and resilience across different topologies amplify agricultural efficiency. Additionally, categorizing WSNs into terrestrial and underground types extends their utility in land assessment and soil monitoring. The amalgamation of WSNs with IoT opens avenues for cost-effective and low-power connectivity among physical entities in agriculture, enabling seamless data transmission and cloud-based processing.

These advancements in agricultural applications, including livestock monitoring, automated irrigation, soil sensing, and weather monitoring, strive to optimize resource utilization and bolster profitability. Addressing the challenge of limited battery capacity in sensor nodes, diverse energy harvesting techniques, particularly solar energy, have emerged. Solar-powered WSNs furnish sustainable and enduring power sources, ensuring self-sufficiency and sustainability in agricultural operations, especially in remote field deployments. This integration marks a watershed moment in technology-driven precision farming, empowering farmers to achieve heightened efficiency and productivity while mitigating environmental impact.

4. CONCLUSION

The integration of wireless sensor networks (WSNs) and the Internet of Things (IoT) in agriculture has revolutionized traditional farming practices, enhancing crop monitoring and resource management. Solar-powered WSNs offer sustainable energy solutions, ensuring self-sufficiency in remote agricultural operations. These technologies pave the way for precision farming practices, enabling real-time monitoring and decision-making for optimal resource utilization. Further research and development in this field are crucial for addressing challenges and unlocking the full potential of technology-driven agriculture.

REFERENCES

5. Abdu, A. I. and Salamah, M. (2011). Energy-aware transmission scheme for wireless sensor networks. In Recent Trends in Wireless and Mobile Networks. Springer, 162, 135-144.
6. Abo-Zahhad, M., Farrag, M., Ali, A. and Amin, O. (2015). An energy consumption model for wireless sensor networks. In : Proceedings of the 2015 International Conference on Energy Aware Computing Systems Applications (ICEAC'15). IEEE, Cairo, Egypt, (pp. 1-4).
7. Akbari, S. (2014). Energy harvesting for wireless sensor networks review. In : Proceedings of the 2014 Federated Conference on Computer Science and Information Systems (FedCSIS). IEEE, (pp. 987-992).
8. Akhtar, F. and Rehmani, M. H. (2015). Energy replenishment using renewable and traditional energy resources for sustainable wireless sensor networks: A review. Renewable and Sustainable Energy Reviews, 45, 769-784.
9. Bader, S., Ma, X. and Oelmann, B. (2014). On the modeling of solar-powered wireless sensor nodes. Journal of Sensor and Actuator Networks, 3, 3, 207-223.
10. Bhangale, SY. and Bhide, AS. (2019). A wireless sensor monitoring node based on automatic tracking solar-powered panel for paddy field environment. International Journal of Advance Research and Innovative Ideas in Education, 5:1522–30.
11. Chieochan, O., Saokaew, A. and Boonchieng, E. (2017). Internet of things (IOT) for smart solar energy: a case study of the smart farm at Maejo University. In: Proceeding 7th Int. Conf. Control. Autom. Inf. Sci., Janua, IEEE (pp. 262–267).
12. Cong Wang, Ji Li, Yuanyuan Yang, Fan Ye. (2017). Combining Solar Energy Harvesting with Wireless Charging for Hybrid Wireless Sensor Networks. IEEE Transactions on Mobile Computing, 17(3), 560-576.
13. Dataflair Team. (2019, November). IoT Applications in Agriculture, 4 Best Benefits of IoT in Agriculture, DataFlair. https://data-flair.training/blogs/iot-applicationsin-agriculture/. [90] Feng, X., Yan, F. and Liu, X. (2019). Study of wireless communication technologies on internet of things for precision agriculture. Wireless Pers Commun, 108:1785–802.

14. Heble, S., Kumar, A., Prasad, KVVD., Samirana, S., Rajalakshmi, P. and Desai, UB. (2018, January). A low power IoT network for smart agriculture. In: Proceeding IEEE World Forum Internet Things, WF-IoT, Institute of Electrical and Electronics Engineers Inc (pp. 609–614).
15. Ilie-Ablachim, D., Patru, GC., Florea, IM. and Rosner, D. (2016, September). Monitoring device for culture substrate growth parameters for precision agriculture: Acronym: MoniSen. In: Proceeding 15th RoEduNet Conference: Networking in Education and Research, IEEE (pp. 1–7).
16. Jawad, HM., Nordin, R., Gharghan, SK., Jawad, AM. and Ismail, M. (2017). Energy-efficient wireless sensor networks for precision agriculture: a review. Sensors (Switzerland), 17:1781.
17. Khanna, A. and Kaur, S. (2019). Evolution of internet of things (IoT) and its significant impact in the field of precision agriculture. Computers and Electronics in Agriculture, 157:218–31.
18. Khattab, A., Abdelgawad, A. and Yelmarthi, K. (2016, December). Design and implementation of a cloud-based IoT scheme for precision agriculture. In: Proceeding 28th Agricultural and Food Sciences, Computer Science, Engineering, IEEE (pp. 201–204).
19. Kiani, F. and Seyyedabbasi, A. (2018). Wireless sensor network and internet of things in precision agriculture. International journal of Advanced Computer Science and Application, 9:99–103.
20. Kumar, SA. and Ilango, P. (2018). The impact of wireless sensor network in the field of precision agriculture: a review. Wireless Pers Commun, 98:685–98.
21. Leah Kelley, C., Gilbertson Eric, Sheikh Anwar, Eppinger Steven, D., Dubowsky Steven. (2010). On the feasibility of solar-powered irrigation. Renewable and Sustainable Energy Reviews, 14(9), 2669-2682.
22. Li, Y. and Shi, R. (2015) An intelligent solar energy-harvesting system for wireless sensor networks. EURASIP Journal on Wireless Communication and Networking, 179, 1–12.
23. Na. A. and Isaac, W. (2016). Developing a human-centric agricultural model in the IoT environment, In: Proceeding Int. Conf. Internet Things Appl. IOTA Institute of Electrical and Electronics Engineers Inc (pp. 292–297).
24. Navulur, S., Sastry, ASCS. and Prasad, MNG. (2017). Agricultural Management through Wireless Sensors and Internet of Things. International Journal of Electrical and Computer Engineering, 7(6), 3492-3499.
25. [108] Nguyen, TD., Thanh, TT., Nguyen, LL. and Huynh, HT. (2015, January). On the design of energy efficient environment monitoring station and data collection network based on ubiquitous wireless sensor networks. In: Proceeding IEEE-RIVF International Conference on Computing and Communication Technologies (pp. 163–168).
26. Nurzaman Ahmed, Debashis De, Iftekhar Hussain. (2018). Internet of things (IoT) for smart precision agriculture and farming in rural areas. IEEE Internet of Things Journal, 5(6), 4890-4899.
27. Ojha Tamoghna, Misra Sudip, Raghuwanshi Narendra Singh. (2015). Wireless sensor networks for agriculture: the state-of-the-art in practice and future challenges. Computers and Electronics in Agriculture, 118, 66-84.
28. Pooja, VN., Pooja, PH., Savitri, GC., Megha, MS. and Nirosha, H. (2017). Design and implementation of agricultural system using solar power. International Journal of Scientific and Research Publication, 7:236–8.
29. Rahul, D.S., Sudarshan, S.K., Meghana, K., Nandan, K.N., Kirthana, R. and Sure, P. (2018, January). IoT based solar powered Agribot for irrigation and farm monitoring: Agribot for irrigation and farm monitoring. In: Proceeding 2nd International Conference Inventive Systems and Control. ICISC. Institute of Electrical and Electronics Engineers Inc. (pp. 826–31).
30. Syafarinda, Y., Akhadin, F., Fitri, ZE., Yogiswara, Widiawanl, B. and Rosdiana, E. (2018). The Precision Agriculture Based on Wireless Sensor Network with MQTT Protocol. IOP Conf Ser Earth Environ Sci 2018;207.
31. Thakur, D., Kumar, Y., Kumar, A. and Singh, P.K. (2019). Applicability of wireless sensor networks in precision agriculture: a review. Wireless Pers Commun, 107:471–512.
32. Vasisht D, Kapetanovic Z, Won J, Jin X, Chandra R, Kapoor A. (2017) In: FarmBeats: An IoT platform for data-driven agriculture. In: Proceeding 14th USENIX Symp Networked Syst Des Implement (pp. 515–529).

33. Vuran, MC., Salam, A,. Wong, R. and Irmak, S. (2018). Internet of underground things in precision agriculture: architecture and technology aspects. Ad Hoc Networks, 81:160–73.
34. Wark, T., Corke, P., Sikka, P., Klingbeil, L., Guo, Y., Crossman, C., Valencia, P., Swain, D. and Bishop-Hurley, G. (2007). Transforming Agriculture through Pervasive Wireless Sensor Networks. IEEE Trans. Pervasive Computing, 6(2), 50-57.
35. Zhang, X., Du, J., Fan, C., Liu, D., Fang, J. and Wang, L. (2017). A wireless sensor monitoring node based on automatic tracking solar-powered panel for paddy field environment. IEEE Internet of Things Journal, 99(4), 1304–1311.
36. Zou, T., Lin, S., Feng, Q. and Chen, Y. (2016). Energy-efficient control with harvesting predictions for solar-powered wireless sensor networks. Sensors, 16:53.