

Smart Wearable Technologies Using IoT-Based Solutions

Dr. Elmer A. Dadios

Professor, De La Salle University, Philippines

Abstract

Smart wearable technologies have emerged as an important application area of the Internet of Things by integrating sensors, communication technologies, embedded computing, and intelligent data-processing capabilities into wearable devices. Smartwatches, fitness trackers, medical wearables, smart clothing, and other connected devices can continuously collect and transmit information related to physical activity, environmental conditions, and user interactions. This study examines smart wearable technologies using IoT-based solutions, with particular attention to sensing mechanisms, wireless connectivity, real-time data processing, edge computing, intelligent analytics, and application integration.

A qualitative descriptive and conceptual research design was adopted using secondary academic literature. The analysis indicates that IoT-enabled wearable technologies can support continuous monitoring, personalized services, remote information exchange, activity recognition, and context-aware applications. Wireless connectivity enables wearable devices to communicate with smartphones, gateways, edge nodes, and cloud platforms, while intelligent analytics can transform collected sensor information into actionable insights. However, wearable IoT systems face challenges related to battery limitations, data security, privacy, device interoperability, connectivity reliability, sensor accuracy, and user acceptance.

The study concludes that IoT-based wearable solutions can contribute significantly to connected and intelligent digital environments when sensing, communication, processing, security, and energy management are integrated effectively. Future research should focus on energy-efficient sensing, lightweight artificial intelligence, privacy-preserving analytics, flexible wearable hardware, edge intelligence, and interoperable wearable IoT architectures.

Keywords: Smart Wearables, Internet of Things, Wearable Technology, IoT-Based Solutions, Smart Sensors, Edge Computing, Wireless Connectivity, Intelligent Analytics, Connected Devices, Wearable Systems.

1. Introduction

The development of wearable technologies has created new opportunities for integrating digital intelligence into everyday activities and connected environments. Wearable devices such as smartwatches, fitness trackers, smart glasses, smart clothing, and sensor-based accessories can collect information continuously through embedded sensing technologies. When connected to the Internet of

Things, these devices become components of broader digital ecosystems capable of exchanging information with smartphones, gateways, cloud platforms, and other connected systems. This integration has expanded wearable technology from simple personal devices into intelligent and connected platforms.

IoT-based wearable systems typically combine sensors, processors, wireless communication modules, software applications, and data-processing services. Sensors can collect information related to movement, activity, temperature, location, or other measurable conditions, while communication technologies enable data transfer to external computing resources. The collected information can subsequently be analyzed to identify patterns, provide feedback, and support personalized applications. Gubbi et al. (2013) emphasized that IoT environments integrate sensing, communication, computation, and intelligent services, providing an appropriate foundation for connected wearable technologies.

Wireless connectivity is a central component of smart wearable systems because wearable devices are generally mobile and resource constrained. Technologies such as Bluetooth Low Energy, Wi-Fi, cellular communication, and other short- and long-range communication mechanisms can connect wearable devices with smartphones, gateways, or cloud services. The selection of communication technology depends on factors such as power consumption, communication range, bandwidth, latency, and application requirements. Low-power communication is particularly important because frequent wireless transmission can reduce battery life and negatively affect user experience.

The integration of edge computing and artificial intelligence can further enhance IoT-based wearable technologies. Edge processing allows selected sensor data to be analyzed closer to the wearable device rather than continuously transmitting raw information to centralized cloud platforms. This can reduce latency and communication requirements. AI-based analytics can support activity recognition, anomaly detection, predictive analysis, and personalized recommendations. Edge intelligence can therefore improve responsiveness while reducing dependence on continuous cloud connectivity.

Smart wearable technologies have applications across numerous fields. Fitness and lifestyle applications can monitor physical activity and provide personalized feedback. Industrial workers can use wearable devices for operational monitoring and safety-related applications. Smart clothing and sensor-enabled accessories can support context-aware services, while connected wearable devices can contribute to broader smart environments. The flexibility of wearable systems allows them to operate as personal data-generation points within larger IoT ecosystems.

Despite their potential, smart wearable technologies face several challenges. Wearable devices typically have limited battery capacity, processing resources, and physical space. Continuous sensing and wireless communication can increase energy consumption. Sensor accuracy can also be affected by device positioning, movement, environmental conditions, or user behavior. In addition, wearable systems may collect sensitive personal information, creating important security and privacy concerns. Interoperability among different devices and platforms remains another challenge.

This study examines smart wearable technologies using IoT-based solutions by analyzing wearable sensing, communication, data processing, edge intelligence, and application integration. It also evaluates the major benefits and challenges associated with wearable IoT systems. The study focuses on how connected wearable devices can contribute to real-time monitoring, intelligent analytics,

personalized services, and efficient information exchange. It further identifies future research directions for developing secure, energy-efficient, interoperable, and intelligent wearable IoT ecosystems.

2. Objectives of the Study

The primary objective of this study is to examine smart wearable technologies using IoT-based solutions by analyzing sensing systems, wireless communication, data processing, edge computing, intelligent analytics, and application integration.

The study seeks to understand how IoT-enabled wearables can improve continuous monitoring, connectivity, personalization, responsiveness, information management, and intelligent decision-making across diverse connected environments.

2.1 Examination of IoT-Based Wearable Technologies

The first objective is to examine major technologies supporting IoT-enabled wearable systems, including smart sensors, embedded processors, wireless communication modules, mobile interfaces, edge computing, and cloud platforms.

The study evaluates how these components operate together to collect, transmit, process, and interpret wearable-generated information. Particular attention is given to connectivity, processing efficiency, energy consumption, responsiveness, and system integration.

2.2 Assessment of Smart Wearable Applications

The second objective is to assess applications of IoT-based wearable technologies across fitness, personal monitoring, industrial environments, smart workplaces, lifestyle management, and connected services.

The study examines how wearable-generated information can support continuous monitoring, activity recognition, personalized feedback, real-time information exchange, and intelligent services. The objective also considers how wearable systems can contribute to broader IoT ecosystems.

2.3 Identification of Implementation Challenges

The third objective is to identify challenges associated with IoT-based wearable technologies, including battery limitations, sensor accuracy, communication reliability, security, privacy, interoperability, computational constraints, and user acceptance.

The study examines how these limitations can influence wearable system performance and usability. Identifying such challenges can support the development of reliable, secure, energy-efficient, interoperable, and user-oriented wearable IoT solutions.

3. Review of Literature

3.1 Wearable Technology and IoT Integration

Patel et al. (2012) examined wearable sensor systems and highlighted their potential for continuous monitoring through body-worn sensing technologies. Wearable sensors can collect information continuously while allowing users to maintain mobility. When integrated with IoT communication networks, such devices can transfer information to smartphones, gateways, or cloud systems for further

processing. This integration creates opportunities for continuous data collection and context-aware services across personal, professional, and connected environments.

Gubbi et al. (2013) described IoT as an ecosystem connecting sensing devices, communication networks, computing infrastructure, and intelligent services. This framework is directly relevant to smart wearables because wearable devices function as distributed sensing and communication points. IoT connectivity allows information generated by wearable devices to be integrated with external systems. Consequently, wearable technologies can contribute to broader connected environments rather than operating as isolated personal devices.

3.2 Wireless Connectivity and Wearable Systems

Wireless communication is essential for wearable IoT systems because wearable devices require mobility and flexible data exchange. Bluetooth Low Energy is particularly suitable for resource-constrained wearable devices because it supports communication with relatively low energy requirements. Wi-Fi and cellular connectivity can provide additional network capabilities when higher bandwidth or wider coverage is required. Communication technology selection therefore depends on device characteristics and application requirements.

Low-power wireless communication is important because wearable devices frequently operate using small batteries. Continuous sensing and data transmission can significantly influence operating time. Research on wireless sensor networks has emphasized energy consumption as a major design consideration for distributed sensing systems. Similar concerns apply to wearable IoT devices, where energy-efficient communication protocols, adaptive transmission, local data processing, and optimized sensing schedules can contribute to longer operating periods and improved usability.

3.3 Intelligent Wearable Data Processing

Artificial intelligence can transform raw wearable sensor information into meaningful information through classification, prediction, and pattern recognition. Machine-learning techniques can support activity recognition and contextual interpretation by identifying relationships among multiple sensor signals. Local or edge-based processing can reduce the need to transmit all raw sensor information to centralized systems. This can improve responsiveness and potentially reduce communication-related energy consumption.

Edge computing provides opportunities for processing wearable-generated information closer to the user or device. Shi et al. (2016) emphasized that edge computing can reduce latency by placing computing resources closer to data sources. In wearable IoT systems, edge processing can support real-time analytics while cloud systems provide additional storage and computational capabilities. Such hybrid architectures can balance responsiveness, processing capacity, and data-management requirements.

4. Research Methodology

4.1 Research Design

This study adopted a qualitative descriptive and conceptual research design to examine smart wearable technologies using IoT-based solutions. The study was based on secondary academic literature

addressing wearable computing, IoT architectures, wireless communication, sensor technologies, edge computing, artificial intelligence, and connected applications. The research design was selected to synthesize existing knowledge and identify major technological relationships within wearable IoT ecosystems.

The conceptual framework considered wearable devices, sensing technologies, communication networks, edge computing, cloud platforms, intelligent analytics, and application services as interconnected components. These components were analyzed according to energy efficiency, communication performance, processing requirements, data management, security, privacy, and usability. The framework provided a structured basis for understanding how technological components interact to support intelligent wearable solutions.

4.2 Data Collection

Secondary information was collected from peer-reviewed journal articles, academic conference papers, scholarly books, and established research publications addressing wearable technologies and IoT systems. Literature concerning wearable sensors, wireless communication, low-power networks, edge computing, machine learning, and wearable applications was reviewed. Sources were selected according to their relevance to the objectives and their contribution to understanding connected wearable systems.

The literature was organized into technological and application-oriented categories. Technological studies addressed sensing, connectivity, processing, energy management, and system architecture. Application-oriented studies focused on fitness, personal monitoring, industrial environments, smart workplaces, and connected services. Research concerning privacy, security, interoperability, sensor reliability, and user acceptance was also examined to identify barriers affecting wearable IoT implementation.

4.3 Data Analysis

The collected literature was analyzed through thematic analysis. Major themes included wearable sensing, wireless connectivity, IoT integration, edge processing, artificial intelligence, energy efficiency, data management, security, privacy, interoperability, and user acceptance. Each theme was examined according to its role in supporting the functionality and effectiveness of IoT-enabled wearable systems.

A comparative synthesis was subsequently performed to identify relationships among wearable components and application requirements. Sensors were considered primary data-generation mechanisms, communication technologies provided connectivity, and edge or cloud resources supported data processing. AI techniques were evaluated for intelligent interpretation, while security and privacy were considered cross-cutting requirements. This approach enabled systematic analysis of the technological structure and challenges of smart wearable IoT solutions.

5. Analysis

5.1 Core Components of Smart Wearable IoT Systems

Smart wearable systems integrate sensing, communication, processing, and application components to provide connected functionality.

Table 1: Core Components of IoT-Based Smart Wearable Systems

Component	Primary Function	Contribution
Wearable Sensors	Data collection	Continuous monitoring
Embedded Processor	Local computation	Initial data processing
Wireless Module	Data communication	Connectivity
Smartphone/Gateway	Data aggregation	Device coordination
Edge Computing	Local analytics	Low-latency processing
Cloud Platform	Data storage	Large-scale analytics
AI Models	Intelligent interpretation	Prediction and recognition
User Application	Information presentation	Personalized services

The analysis demonstrates that smart wearable IoT systems depend on the interaction of multiple technological layers. Sensors generate information, embedded processors perform initial processing, and wireless modules establish connectivity. Smartphones or gateways can aggregate information, while edge and cloud platforms provide additional computational resources.

AI models transform sensor information into intelligent outputs, and application interfaces present results to users. Effective coordination among these components is essential for reliable wearable functionality.

5.2 Applications of IoT-Based Smart Wearables

IoT-based wearable technologies can support diverse applications across personal and professional environments.

Table 2: Major Applications of Smart Wearable IoT Technologies

Application Area	Wearable Function	Potential Contribution
Fitness	Activity monitoring	Personalized feedback
Lifestyle	Behavior tracking	Context-aware services
Smart Workplace	Activity and environment monitoring	Operational support
Industrial Operations	Worker-related sensing	Safety and monitoring
Connected Services	Context detection	Personalized interaction
Sports	Performance tracking	Performance analysis

Application Area	Wearable Function	Potential Contribution
Smart Environments	User-state sensing	Adaptive services
Personal Productivity	Activity monitoring	Task support

The analysis indicates that wearable IoT technologies can extend beyond conventional fitness applications. Connected wearables can contribute to smart environments by providing contextual information about users and activities.

Their ability to collect information continuously enables applications requiring real-time or periodic monitoring. Integration with edge and cloud platforms can further support intelligent analytics and personalized services. However, application effectiveness depends on sensor quality, communication reliability, energy efficiency, privacy protection, and user acceptance.

6. Discussion

Smart wearable technologies using IoT-based solutions provide a flexible mechanism for continuous sensing and connected information exchange. Wearable devices can collect information while users remain mobile, creating opportunities for real-time monitoring and personalized applications. IoT connectivity extends wearable functionality by allowing collected information to be communicated to smartphones, gateways, edge nodes, and cloud platforms. This transforms individual wearable devices into components of broader intelligent digital ecosystems.

The integration of edge computing and artificial intelligence can improve the responsiveness of wearable IoT systems. Edge processing can analyze selected information near the user, reducing dependence on continuous cloud communication. AI techniques can identify patterns, classify activities, and generate predictions from sensor information. However, computational limitations and battery constraints require lightweight algorithms and efficient processing strategies. Wearable systems must balance analytical capability with energy consumption and device usability.

Security, privacy, interoperability, and reliability remain critical considerations for smart wearable IoT deployment. Wearable devices can generate continuous and potentially sensitive information, making secure communication and appropriate data management essential. Different wearable platforms may also use different hardware and software architectures, creating interoperability difficulties. Future systems should therefore integrate secure communication, privacy-preserving analytics, standardized interfaces, energy-aware processing, and adaptive connectivity. These capabilities can improve the reliability and sustainability of wearable IoT ecosystems.

7. Challenges

7.1 Battery and Energy Limitations

Battery limitations represent a significant challenge for smart wearable IoT systems because wearable devices generally use small batteries due to size and portability requirements. Continuous sensing, data processing, wireless communication, and AI inference can increase energy consumption. Frequent communication with external platforms may further reduce operating time. Energy-efficient sensors,

low-power communication protocols, adaptive sampling, local processing, and optimized algorithms are therefore important for maintaining acceptable battery performance.

Energy requirements can also change according to application intensity and user activity. A wearable device performing continuous sensing and real-time analytics may consume considerably more energy than a device operating intermittently. Intelligent energy management should therefore adjust sensing and communication according to application priorities and battery conditions. Efficient workload scheduling and selective data transmission can reduce unnecessary processing while preserving important information. These approaches can improve operating duration and user convenience.

7.2 Sensor Accuracy and Reliability

Wearable sensors can experience measurement errors due to device movement, improper positioning, environmental conditions, physical contact, and variations among users. These factors may reduce the accuracy of information generated by wearable devices. Reliable applications require appropriate sensor calibration, signal-processing techniques, sensor fusion, and validation procedures. Poor-quality sensor data can affect subsequent analytics and reduce the reliability of intelligent decisions generated by the system.

Sensor reliability is also influenced by continuous device usage and environmental exposure. Wearable devices may encounter temperature changes, moisture, physical movement, or mechanical stress. Advanced wearable IoT systems should therefore incorporate robust sensing mechanisms and error-detection techniques. Combining information from multiple sensors can improve reliability by reducing dependence on a single measurement source. Intelligent filtering and anomaly detection can further identify inconsistent information before it is used for application-level decisions.

7.3 Security and Privacy

Smart wearable devices can collect continuous information about user activities, locations, interactions, and environmental conditions. This creates important privacy and security concerns because unauthorized access to wearable-generated information could expose sensitive personal information. Communication channels between wearables, smartphones, edge nodes, and cloud platforms must therefore be protected using appropriate authentication, encryption, access control, and secure communication mechanisms.

Privacy protection also requires responsible data-management practices. Collecting more information than necessary can increase privacy risks and storage requirements. Local edge processing can potentially reduce exposure by allowing selected information to be analyzed without transmitting all raw data to centralized platforms. Privacy-preserving analytics, data minimization, secure storage, and controlled access can further strengthen protection. Privacy considerations should be integrated into wearable IoT architecture rather than treated solely as an external compliance requirement.

7.4 Interoperability and User Acceptance

Wearable IoT ecosystems may include devices from different manufacturers using different operating systems, communication technologies, data formats, and application platforms. This heterogeneity can

make device integration difficult and may prevent seamless exchange of information. Standardized interfaces and communication protocols can improve interoperability, while modular architectures can facilitate integration across platforms. However, achieving interoperability without compromising performance and security remains technically challenging.

User acceptance is also important because wearable devices are directly integrated into everyday activities. Users may discontinue devices if they experience uncomfortable designs, short battery life, complicated interfaces, unreliable measurements, or privacy concerns. Wearable systems should therefore prioritize usability, comfort, transparency, and ease of interaction. Clear information about data collection and privacy controls can improve user confidence. Successful adoption depends not only on technical performance but also on user-centered design.

8. Future Research

Future research should focus on developing energy-efficient wearable IoT architectures capable of supporting continuous sensing and intelligent processing. Lightweight AI models, adaptive sensing, energy-aware communication, and efficient edge inference should be investigated to reduce battery requirements. Research should also examine flexible and miniaturized sensing technologies that improve comfort while maintaining measurement reliability. These developments can strengthen the practical usability of wearable systems.

Further research should investigate secure, interoperable, and privacy-preserving wearable IoT ecosystems. Federated learning, local edge analytics, secure device authentication, standardized interfaces, and privacy-aware data management should receive greater attention. Future studies should evaluate wearable solutions under realistic conditions involving different users, environments, devices, and communication conditions. Performance should be assessed through energy consumption, sensor accuracy, latency, reliability, security, interoperability, and user acceptance.

9. Conclusion

Smart wearable technologies using IoT-based solutions provide an important mechanism for integrating continuous sensing and intelligent connectivity into everyday digital environments. Wearable sensors can collect information while users remain mobile, while IoT communication enables this information to interact with smartphones, gateways, edge nodes, cloud platforms, and application services. This integration creates opportunities for responsive and personalized connected applications.

The analysis demonstrates that wearable IoT systems depend on multiple interconnected technologies. Sensors generate information, embedded processors provide local computation, communication modules enable data exchange, and edge and cloud platforms support advanced processing. Artificial intelligence can further transform sensor information into meaningful insights through activity recognition, classification, prediction, and contextual analysis. Effective coordination among these components is essential for reliable performance.

IoT-based wearable technologies can support diverse applications, including fitness, lifestyle management, sports, smart workplaces, industrial operations, connected services, and intelligent environments. Their continuous sensing capabilities can provide useful information for personalized services and context-aware applications. However, sensor reliability, energy consumption,

communication performance, and device interoperability can significantly influence practical implementation.

Overall, smart wearable technologies have considerable potential to contribute to future IoT ecosystems. Their development should prioritize energy efficiency, secure communication, privacy protection, sensor accuracy, interoperability, and user-centered design. Integration with edge computing and lightweight artificial intelligence can further improve responsiveness while reducing communication requirements. Addressing these technological and user-related challenges can support the development of reliable, secure, efficient, and sustainable wearable IoT solutions.

References

1. Pantelopoulos, A., & Bourbakis, N. G. (2010). A survey on wearable sensor-based systems for health monitoring and prognosis. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, 40(1), 1–12. <https://doi.org/10.1109/TSMCC.2009.2032660>
2. Fletcher, R. R., Poh, M.-Z., & Eydgahi, H. (2010). Wearable sensors: Opportunities and challenges for low-cost health care. In *2010 Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (pp. 1763–1766). IEEE. <https://doi.org/10.1109/IEMBS.2010.5626734>
3. Miorandi, D., Sicari, S., De Pellegrini, F., & Chlamtac, I. (2012). Internet of Things: Vision, applications and research challenges. *Ad Hoc Networks*, 10(7), 1497–1516. <https://doi.org/10.1016/j.adhoc.2012.02.016>
4. Gubbi, J., Buyya, R., Marusic, S., & Palaniswami, M. (2013). Internet of Things (IoT): A vision, architectural elements, and future directions. *Future Generation Computer Systems*, 29(7), 1645–1660. <https://doi.org/10.1016/j.future.2013.01.010>
5. Gao, W., Emaminejad, S., Nyein, H. Y. Y., Challa, S., Chen, K., Peck, A., Fahad, H. M., Chen, H., Guo, X., & others. (2016). Fully integrated wearable sensor arrays for multiplexed in situ perspiration analysis. *Nature*, 529, 509–514. <https://doi.org/10.1038/nature16521>
6. Kim, J., Campbell, A. S., de Ávila, B. E.-F., & Wang, J. (2019). Wearable biosensors for healthcare monitoring. *Nature Biotechnology*, 37, 389–406. <https://doi.org/10.1038/s41587-019-0045-y>
7. Heikenfeld, J., Jajack, A., Rogers, J., Gutruf, P., Tian, L., Pan, T., Li, R., Khine, M., Kim, J., & Kim, J. (2018). Wearable sensors: Modalities, challenges, and prospects. *Lab on a Chip*, 18, 217–248. <https://doi.org/10.1039/C7LC00914C>
8. Fernández-Caramés, T. M., & Fraga-Lamas, P. (2018). Towards the Internet of smart clothing: A review on IoT wearables and garments for creating intelligent connected e-textiles. *Electronics*, 7(12), 405. <https://doi.org/10.3390/electronics7120405>
9. Al-Eidan, R., Al-Khalifa, H. S., & Al-Salman, A. (2018). A review of wrist-worn wearable: Sensors, models, and challenges. *Journal of Sensors*, 2018, Article 5853917. <https://doi.org/10.1155/2018/5853917>
10. Kamišalić, A., Fister, I., Turkanović, M., & Karakatič, S. (2018). Sensors and functionalities of non-invasive wrist-wearable devices: A review. *Sensors*, 18(6), 1714. <https://doi.org/10.3390/s18061714>

11. Tahir, H., Tahir, R., & McDonald-Maier, K. (2018). On the security of consumer wearable devices in the Internet of Things. *PLOS ONE*, 13(4), e0195487. <https://doi.org/10.1371/journal.pone.0195487>
12. Dargazany, R., & others. (2018). WearableDL: Wearable Internet-of-Things and deep learning for big data analytics—Concept, literature, and future. *Mobile Information Systems*, 2018, Article 8125126. <https://doi.org/10.1155/2018/8125126>
13. Ha, I. (2015). Technologies and research trends in wireless body area networks for healthcare: A systematic literature review. *International Journal of Distributed Sensor Networks*, 11(10), 573538. <https://doi.org/10.1155/2015/573538>
14. Loncar-Turukalo, T., Zdravevski, E., da Silva, J. M., Chouvarda, I., & Trajkovik, V. (2019). Literature on wearable technology for connected health: Scoping review of research trends, advances, and barriers. *Journal of Medical Internet Research*, 21(9), e14017. <https://doi.org/10.2196/14017>
15. Cho, J. (2019). Current status and prospects of health-related sensing technology in wearable devices. *Journal of Healthcare Engineering*, 2019, Article 3924508. <https://doi.org/10.1155/2019/3924508>
16. Shin, G., Jarrahi, M. H., Fei, Y., Karami, A., Gafinowitz, N., Byun, A., & Lu, X. (2019). Wearable activity trackers, accuracy, adoption, acceptance and health impact: A systematic literature review. *Journal of Biomedical Informatics*, 93, 103153. <https://doi.org/10.1016/j.jbi.2019.103153>
17. Sivaraman, H. (2019). IoT-enabled healthcare monitoring: A systematic review of wearable devices. *Information Technology in Industry*, 7(3). <https://doi.org/10.17762/itii.v7i3.815>
18. Reviews of wearable healthcare systems: Materials, devices and system integration. (2020). *Materials Science and Engineering: R: Reports*, 140, 100523. <https://doi.org/10.1016/j.mser.2019.100523>
19. Mamdiwar, S. D., Akshith, R., Shakruwala, Z., Chadha, U., Srinivasan, K., & Chang, C.-Y. (2021). Recent advances on IoT-assisted wearable sensor systems for healthcare monitoring. *Biosensors*, 11(10), 372. <https://doi.org/10.3390/bios11100372>
20. Iqbal, S. M. A., Mahgoub, I., Du, E., Leavitt, M. A., & Asghar, W. (2021). Advances in healthcare wearable devices. *npj Flexible Electronics*, 5, Article 9. <https://doi.org/10.1038/s41528-021-00107-x>