International Journal of Robotics and Control Systems
Vol. 6, No. 1, 2026, pp. 718-740
ISSN 2775-2658
http://pubs2.ascee.org/index.php/ijrcs

Sustainable Green Unmanned Aerial Vehicles (UAV) Systems for Smart and Environmental Applications: A Review

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ARTICLE INFO

Article History
Received November 22, 2025
Revised January 05, 2026
Accepted March 12, 2026

Keywords
Sustainable Green UAVs;
Energy-Efficient UAV Systems;
Intelligent UAVs;
Renewable Energy Harvesting;
Smart City Applications;
Environmental Monitoring;
UAV Sustainability Taxonomy

ABSTRACT

Unmanned Aerial Vehicles (UAVs), as a unique enabler, have been widely used for smart city and environmental applications owing to their agility, flexibility, and large-scale sensing capability. Nevertheless, the widespread and long-term use of such systems is restricted by the energy stored on board, impact on the environment as well as sustainability issues. Existing survey work is primarily aimed toward energy or communication efficiency, and a holistic sustainable prospective is not yet to be found. Research contribution The research contribution is a review of usable (sustainable green) UAV systems for smart and the environmental applications with categorisation (taxonomy) which systematically categorises existing work. Recent literature is structured along sustainability scope, green enabling technology, level of intelligence, application domains, evaluation methods and performance metrics. A systematic literature review of peer-reviewed articles published between 2019 and 2025 was carried out. The results reveal that about 75% focus on operational energy efficiency, less than a quarter cover security, privacy or trust aspects, and less than 20% full lifecycle sustainability. Recent developments are witnessing the convergence of AI,energy harvesting (EH) and edge computing to enhance the endurance and autonomy of UAVs. However, the structured evaluation frameworks, long-term real-world validation, and integrated sustainability-aware designs are still some of the challenges. The current review in playing a balancing role is expected to bridge this gap by highlighting some of the significant research gaps and strategic directions that can steer the development of cost-effective, intelligent and environmentally benign UAV systems.

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https://dx.doi.org/10.31763/ijrcs.v6i1.2455
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1. Introduction

Unmanned Aerial Vehicles (UAVs) are experiencing a rapid development and becoming an enabling technology for smart and environment applications, including smart city observation, environment monitoring, precision agriculture management, disaster relief inspection and critical infrastructure checking [1], [2]. With their fast deployment, flexible mobility and high view from the sky, it can execute services that are hard to perform or expensive by conventional ground systems [3]–[7]. Nevertheless, the large-scale application of UAVs leads to serious issues concerning energy resource constraint, environmental pollution, operation fee and even sustainability [8], [9].

Traditional UAV systems are generally limited by short flight time, frequent battery change and high energy consumption, which is dominated by propulsion, sensing, communication and onboard computing [10]–[15]. These limitations not only impose limited time and area upon mission performances but lead to environmental and economical problems associated with repeated charging or discharging, battery fatigue, and emission of non-renewable energy [16]–[18]. Consequently, sustainability has been identified as a key design requirement not just a secondary in modern UAV development [19], [20].

In recent years, solar-assisted propulsion, new materials, energy-aware trajectory planning and AI-based optimization techniques have been developed in order to improve UAV endurance and autonomy [21]–[23]. In addition to that, edge and fog computing paradigms take one step further in minimizing the communication overhead and energy consumption by supporting local data processing and real-time decisions [24]–[26]. However, current survey works tend to concentrate on individual aspects such as energy efficiency, communication performance or UAV networking and do not offer a global perspective devoted to the concept of sustainability [27]–[30]. In particular, the interplay between sustainability, intelligence, application needs and security is not yet studied in a comprehensive manner [31]–[33].

This gap calls for a systematic review of sustainable green UAV research, which goes beyond one-dimensional optimisation. Differing from previous surveys, sustainability is emphasized as a multi-facet concept comprising of operational energy efficiency, environmental footprint, intelligent degree scope and coverage evaluation methodologies and performance metrics. By synthesizing these dimensions, the review contributes valuable knowledge on state-of-the-art directions in research topics and dominating design choices, as well as on underinvestigated challenges including lifecycle sustainability analysis, standard benchmarking methodology, and security-aware UAS designs.

The novelty of the research is to present a holistic, sustainable-oriented review for green UAV systems tailored for smart and environmental applications rather than standard energy-efficient surveys. In this paper, a structured multi-dimension taxonomy that systematically categorises the current efforts is developed based on six main dimensions: -sustainability scope, green enabling technologies, degree of intelligence, application domains and evaluation and validation methods and performance metrics. In contrast to related work which tend to cover separate aspects, including the study (e.g., energy consumption and communication efficiency) as clearly computerized oriented tasks, this study gives a comprehensive view on the research for discovering dominant trends of research, comparative benefits, and open challenges. Particularly, it emphasizes the insufficient attention paid to lifecycle sustainability, security, privacy and trust in exisiting UAV research. By providing taxonomy-driven synthesis and strategic insights, this review represents a practical reference framework for informing future studies and innovations toward scalable, intelligent, eco-friendly UAV systems.

The remainder of this paper is organized as follows. Section 2 shows the process of methodology. Section 3 presents the background and fundamental concepts of sustainable UAV systems in terms of sustainable green UAV architectures, intelligent and AI-enabled UAV systems, sustainable UAV applications,and security, privacy, and trust issues. Section 4 provides a taxonomy of sustainable green UAV research studies. Section 5 provides a taxonomy-based analysis of strengths and limitations, and

Section 6 shows results and discussion of this paper. Section 7 outlines open challenges and future research directions. Finally, Section 8 concludes the paper.

2. Review Methodology

This investigation proceeds via a structured narrative review rather than a full systematic literature review. It is not for an exhaustive review of all publications, but to provide conceptual synthesis, taxonomy construction and comparative analysis related to representative research on a green sustainability in Smart & environmental applications using UAV systems.

- Literature Identification: Relevant publications were searched in the major online scientific databases, such as IEEE Xplore, Elsevier (ScienceDirect), SpringerLink and MDPI dataset. The search was conducted for the recent papers published in peer-reviewed journals and conference proceedings applying different keywords as sustainable UAV, green UAV, energy efficient UAV, solar powered UAV, intelligent UAV and sustainability of small UAS. Whenever possible, priority was given to works published from 2019-2025 in order to reflect the most current trends and new developments.
- Study Selection and Scope: Studies were selected according to their relevance based on the goals of the review rather than a strict set of inclusion–exclusion criteria. Studies were included if they addressed at least one sustainability dimension, i.e., energy efficient technologies for control of buildings, integration of renewable energy sources in smart homes and utilisation, application-oriented deployment of solutions and sustainability-aware evaluation thereof. Studies related to only military UAV operations or without technical contents were excluded. This process identified 64 exemplar studies to inform taxonomy development and comparisons.
- Taxonomy Construction and Analysis: The taxonomy was constructed through an iterative qualitative analysis on the selected literature. Normalized findings revealed common themes, design objectives and evaluation techniques that were grouped into six dimensions of sustainability scope, green enabling technologies, intelligence level, application domains centered on their use cases, evaluation and validation approaches and associated success metrics. Individual studies were charted on these dimensions to compare across category and identify predominant research areas, strengths and weaknesses.
- Methodological Limitations: Because of the nature of a narrative review, we do not purport to provide completeness and there is potential for publication bias, or database limitation. However, we believe that the approach taken here presents a fair and transparent overview of existing research trajectories, and provides an adaptable framework which can be extended as further studies are conducted.

3. Background and Fundamentals

This is why this section describes the necessary background and basic ideas for a comprehensive understanding of green sustainable UAV architectures. It presents basic UAV concepts, sustainability dimensions and the technological backdrop that lies behind energy-efficient, intelligent and environmentally-friendly UAV operations in smart and environmental applications. Having set this context, the section sets stage for the latter discussions on sustainable UAV architecture, AI-assisted intelligence, application domains and security considerations in the next sections.

3.1. Overview

This the basic background information necessary to understand sustainable green UAV systems, as shown in Fig. 1. It covers fundamental UAV knowledge, sustainability principles, and the technological background to understand energy-efficient intelligent and environmentally friendly UAV work in smart and environmental applications.

Fig. 1. Overview of background and fundamental concepts for sustainable green UAV systems

- Unmanned Aerial Vehicles Concepts and Classification: Introduction Unmanned Aerial Vehicles (UAVs), also known as drones, are a type of aircraft system that can be operated independently or partially independently from an onboard human pilot. According to design configuration and characteristics of flight, UVAs are broadly divided into fixed-wing, rotary-wing and hybrid ones [34]–[36]. Fixed-wing UAVs have merits of long endurance and high energy efficiency for distant missions, meanwhile rotary-wing UAVs can hover and fly stably in relatively short distant thus are more suitable for close-range sensing and inspection. Hybrid UAVs have the goal of combining both benefits, vertical take off and landing as well as efficient forward flight [37]–[39].
- Energy Consumption and Sustainability Issues in UAV Systems: Although UAVs are maneuverable, they suffer from energy resource restrictions. Power requirements are dominated by propulsion, and in lesser extent for sensing, communication and onboard computing. Such limitations impact the flight endurance, area of coverage and mission reliability [40]. Sustainability-wise, repeated change of batteries, aggressive charging, and emission due to conventional energy sources have raised the issue on the green effect and financial burden, which in turn drives emerging energy-efficient and environment-friendly UAV solutions [41], [42].
- Basics of Sustainability in UAV Systems: UAV systems as a whole are becoming sustainable, not only in terms of energy consumption but also from environmental, economic and operational perspectives. From an environmental perspective, sustainable UAVs seek to minimize C emissions, noise pollutant and land ecological impact. In economic terms, sustainability dictates low-of-cost /low maintenace / long life systems. Operational sustainability is targeting longer duration missions, reliability and flexibility in evolving environments. These sustainability dimensions provide a path for the convergence in designing green UAV architectures and intelligent control [43], [44].
- Fundamentals of UAV Communication, Computing, and Networking: Wireless communication and data processing are of great concerns for the current UAV applications. UAVs are commonly used as sensing platforms, aerial relays or edge nodes of a larger network. Communication protocols, transmission power control and networking topology play key roles in energy expenditure and system performance. Joint UAVs-edge/fog computing systems allow for real-time information processing, edge data offloading and control decision support, thereby sustain the operation of green systems through limiting communication overhead.

- Why Sustainable and Smart UAV Design Matters: The emerging energy limitations, environmental pressures and growing applications have driven the investigation of renewable intelligent UAV system. New approaches to grid systems, materials, AI and edge computing are opening up new possibilities that could help overcome traditional constraints. A good understanding of these fundamental issues is necessary for the analysis of the current literature, development of new taxonomies and also in identifying future trends towards scalable and environmental friendly UAV deployments.

In short, the background and basics presented in this section provide a technical theoretical foundation for sustainable green UAV research. They provide the context required for the architectural, intelligent, application-oriented, and security-based discussions that follow along this review's sections.

3.2. Sustainable Green UAV Architecture

The design of the environmentally friendly UAV system is also vital for long endurance operation, low environmental pollution and mission task performance, as shown in Fig. 2. Contrary to state of the art UAV designs that focus on flight efficiency, sustainable UAV solutions also include energy efficient and modular system design including airframe, power plant design and communication as well as onboard intelligence. An integrated approach that ranges from the architecture to balancing of sustainability goals versus operational needs is crucial.

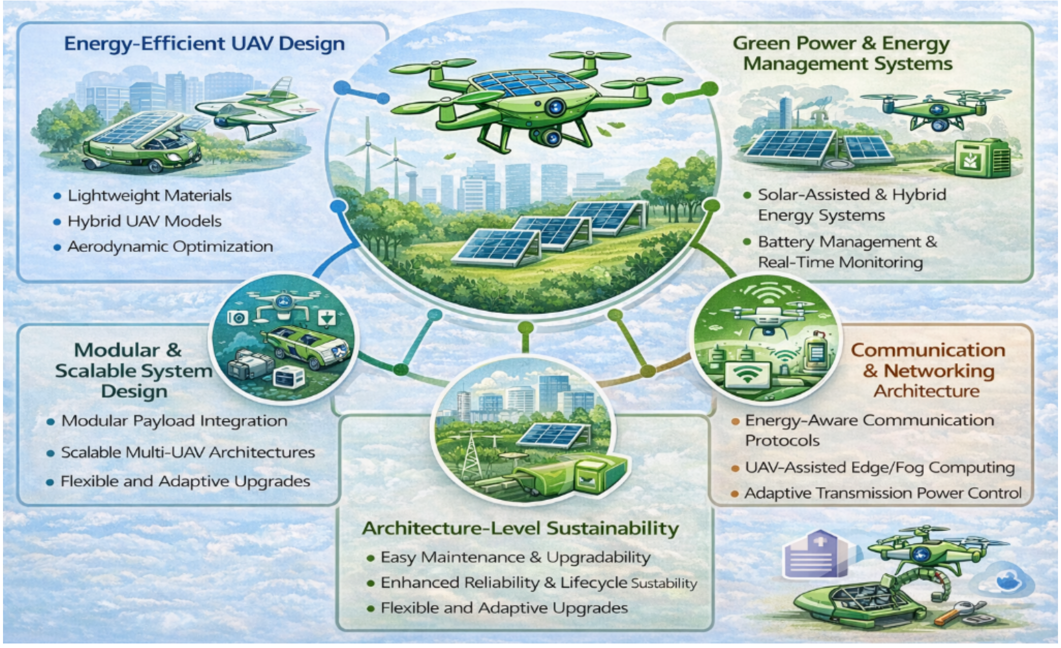

Fig. 2. Conceptual architecture of sustainable green UAV systems

- Energy-Efficient UAV Design: Construction of energy efficient architecture is the basis of sustainable UAV design. The most commonly used solutions to reduce propulsion power consumption are through-put reduction (lightweight materials, aerodynamic optimization and payload-driven structural design). The choice of fixed-wing, rotary -wing and hybrid UAV architectures are made according to mission specifications, where the preference is towards hybrid designs due to their advantage in achieving a good trade-off between hover capability and endurance for long-range missions. The design of such vehicles significantly affects flying time, energy consumption and environmental impact.
- Green Power and Energy Management Systems: Green power plants and subsystems are indis-

pensable for sustainable UAV missions. Solar-assisted/hybrid systems add renewable energy to the mix with onboard batteries such that a mission could last longer and rely less on ground charging facilities. Sophisticated energy management systems track the health of the battery, energy-harvest and consumption rates in real-time and optimally distribute resources while avoiding extraneous power waste throughout flight and sensing missions.

- Communication and Networking Architecture: The communication architecture is a critical factor in UAV energy consumption, especially in data-heavy use cases. Long-lived UAV frameworks deploy energy conscious communication protocols, online power control of transmission and aerial networking to minimize the communication overhead. The coupling of UAVs with E/F-CI also indirectly helps in sustainable operation by allowing local data processing and reducing the long-range data transfer to cloud servers.
- Modular and Scalable System Design: Modularity and scalability are the essential architecture properties to drive for sustainable UAV systems. The modularized system provides an adaptable Sensor/Power/Communication so lution which can be modified incrementally without the need to re-design the complete platform. Scalability is a key factor for the design of multi UAV systems, where coordinated architectures ensure cooperation in sensing, load balancing, and energy-aware task allocation while preserving the overall system efficiency.
- Architecture-Level Sustainability Considerations: At another level, sustainability in architectural design includes considerations which cut across energy efficiency, such as system reliability, maintainability and lifecycle impact. Developing UAV topologies to accommodate maintenance, service of components, and software updates can extend the life of the system as well as reduce adverse environmental waste. Such architectural decisions are crucial for the realization of sustainable UAV systems in long-term smart city and environmental monitoring use cases.

In a nutshell, sustainable Green UAV architecture is the substrate on which energy-efficient, intelligent and application-oriented UAV systems rest. Through combining green power systems accompanied with energy-aware communication and modularity, such architectures facilitate scalable and eco-friendly UAV deployments.

3.3. Intelligent and AI-Enabled Sustainable UAVs

The inclusion of AI has played a crucial role in promoting the sustainability of contemporary UAV systems. Intelligent UAVs can sense the environment, learn through operational data and adjust their behavior in real-time, resulting in remarkable enhancement of energy efficiency, autonomy and mission effectiveness. AI-based solutions provide more flexibility for the complex energy performance and operational reliability trade-off compared to rule-based or static optimization techniques.

- AI-Based Energy Optimization and Control: UAV energy consumption, battery degradation and flight endurance are modeled and forecast using machine learning methodologies. Data driven models ensure high-fidelity of power use estimation across different flight conditions, loads and environments, facilitating the opportunity for predictive energy management and longer battery life. These functions enable the UAVs to automatically adapt their speed, altitude, and sensing frequency in real time in order to reduce the wastage of energy.
- Reinforcement Learning for Unmanned Aerial Vehicles (UAVs) Towards Autonomous and Adaptive Operations: Reinforcement learning (RL) has been identified as an effective means to enable autonomous decision in sustainable UAV systems [45], [46]. Through interaction with environment and finding optimization policies, the RL-based UAVs can realize energy-efficient trajectory planning, mission scheduling and resource allocation without pre-defined models. In multi-UAV systems, coordination efficiency, coverage performance and total energy consumption are significantly improved through cooperative or multi-agent RL approaches in both large-scale and dynamic environments [47], [48].
- Edge-Intelligent UAV Systems: Edge intelligence is pivotal to reducing communications overhead

and latencies in UAV-enabled applications. With on-UAV or near-edge data processing and inference, intelligent UAVs can bound the raw data transmitted to cloud servers, saving energy while maintaining privacy. Edge-AI pipelines enable decision-making in real time for object detection, anomaly detection and adaptive sensing, which are the essential element of sustainable smart city and environmental monitoring applications [49].

- Challenges and Trade-Offs: AI-based UAV systems come at the cost of computational and model training overhead. This is why lightweight and energy-aware AI models are required, to avoid that what we gain in intelligence comes at the cost of sustainability gains. How to strike a balance between the accuracy and autonomy of learning as well as energy-efficiency is still an open research challenge, particularly for long-lasting resource constrained UAV deployments.

Finally, smart and AI-supported UAVs are a cornerstone in sustainable aerial systems. Through the incorporation of AI, which provides higher level reasoning and decision-making capabilities, adaptive control over predictive energy management along with efficient cooperation, scalable autonomous and green UAV operation can be achieved.

3.4. Sustainable UAV Applications

Highly sustainable green UAVs are increasingly becoming crucial enablers throughout multiple smart and environmental application areas. Energy-aware design allows green UAVs to be highly flexible and rapidly deployable while also requiring only a fraction of the energy and environmental damage of regular systems. The integration of renewable energy sources, energy-aware control, and intelligent decision-making unlock access to long-term, large-scale operations in instances when low patient endurance and high costs caused the service to be impossible or detrimental to the environment. Table 1 summarizes the main application domains of sustainable UAV systems and highlights the corresponding sustainability techniques, enabling technologies, and achieved benefits.

Table 1. Summary of sustainable UAV application domains and associated sustainability techniques

Application Domain	Sustainability Techniques	Enabling Technologies	Key Benefits
Smart Cities	Energy-aware trajectory planning, edge processing, adaptive sensing	Solar-assisted UAVs, edge/fog computing, lightweight sensors	Reduced energy consumption, scalable urban monitoring, lower emissions
Environmental Monitoring	Renewable energy harvesting, energy-efficient sensing, long-endurance flight	Solar-powered UAVs, low-power sensors, optimized communication	Persistent monitoring, reduced ecological footprint, wide-area coverage
Precision Agriculture	Optimized coverage planning, energy-efficient clustering, adaptive flight scheduling	UAV-based sensor networks, AI-driven analytics, GPS-assisted navigation	Lower operational cost, resource-efficient farming, extended mission duration
Disaster Response and Emergency Management	Energy-aware deployment, adaptive path planning, cooperative UAV coordination	Multi-UAV systems, ad hoc communications, renewable energy support	Rapid response, improved coverage, resilience under limited infrastructure
Smart Infrastructure and Energy Systems	Autonomous navigation, optimized inspection scheduling, energy-efficient hovering	Computer vision, AI-based fault detection, edge intelligence	Reduced maintenance cost, enhanced inspection frequency, improved safety

- Smart City Applications: In urban smart cities, sustainable UAVs are frequently used for monitoring traffic, city surveillance, inspection of infrastructure and services that provide public safety. Flight planning for energy-efficient UAVs, coupled with lightweight sensing enables deployment of UAVs in either persistent or intermittent monitoring modes that enable power and emission-aware operation [50]–[52]. Solar-power-assisted UAVs and UAV-helper edge computing further cut down data transmission overhead, involving no men nor materials in the process of carrying out local processing and contributing to a scalable and green urban sensing infrastructure [53],

[54].

- Environmental Monitoring and Protection: One of the most interesting applications of sustainable UAVs is in the field of environment. Green UAVs are applied for air quality and pollution monitoring, wildfire detection, wildlife protection and climate watching [55]–[57]. Solar-powered (or battery-efficient) UAVs ensure a persistent screening of large territories, and energy- aware sensing and communication minimises the ecological imprint and overall footprint, by which they become particularly well-suited to perform environmental protection operations in terms of unobtrusiveness and duration [58], [59].
- Precision Agriculture: In precision agriculture, sustainable UAV-s used for efficient crop monitoring and irrigation management as well as soil analysis and yield costs are. Energy efficient UAV-based sensor networks with coverage optimization reduce the flight redundancy, which prolongs mission time [60]–[62]. These techniques reduce operational costs, protect resources such as water or fertilizers and there by promoting environmentally friendly farming practices [63], [64].
- Disaster Response and Emergency Management: Disaster response, such as search and rescue, assessment of damage, and emergency communication; depends heavily on sustainable UAV systems [65], [66]. Energy-aware deployment method and adaptive path planning help the UAVs to fly in inhospitable environment with scarce charging facilities. The utilization of renewable energy and energy-aware coordination enhances the reliability and responsiveness of missions with reduced logistical-and environmental-bound limitations [67]–[69].
- Smart Infrastructure and Energy Systems: UAVs have been increasingly employed in the inspection and monitoring of smart infrastructures, e.g., power lines, pipelines, bridges and renewable energy resources [70], [71]. Energy-efficient UAV designs lower the rates of maintenance and environmental exhaust, as they allow for assessments to occur often without requiring ground-based retrievals. Energy-aware algorithms and autonomy lead to scalability, making UAVs an attractive candidate for smart grid and critical infrastructure surveillance [72], [73].

In general, sustainable UAV applications show that energy-conscious design, intelligent control and green technology can work together to serve a wide range of existing services. Such application-oriented research emphasises the societal and environmental advantages of green UAV technology, and underscores the need for sustainability as an essential design feature rather than a secondary consideration.

3.5. Security, Privacy and Trust in Sustainable UAV Systems

Security, privacy, and trust are key enablers for the reliable deployment of sustainable green UAV systems, especially in smart city and environmental contexts, as shown in Fig. 3. Though many endeavors have been made for achieving high energy efficiency and long endurance, it is still difficult to implement complex security mechanisms in MCU-limited UAV platforms. Artificial security solutions usually result in a significant increase of computational, communication and energy costs that could be contrary to sustainability goals.

From the security point of view, sustained UAV systems face a number of potential threats such as eavesdropping, spoofing, jamming, false data injection, unauthorized access etc. Not only mission reliability may be affected, such attacks can as well result in a waste of energy from retransmissions, recovery process or even mission failures. Recent work, therefore, focuses on lightweight authentication, energy-efficient key establishment schemes and secure communication protocols which offer a good trade off between security and power consumption.

Privacy protection is also of the same significance in UAV-enabled sensing and monitoring applications for example, sensitive data such as location, images capturing and personal information would collected. Lack of secure communications may hinder the public acceptance and regulatory compliance for green UAV systems. Novel solutions shift towards the goal of reducing data exposure which can be achieved by performing edge processing, applying anonymization techniques and selective sharing of data - leading to reduced privacy risk as well as easier communication exchange.

Fig. 3. Conceptual illustration of security, privacy, and trust challenges and solutions in sustainable UAV systems

Trust management is an important factor in multi-UAVs and UAV-assisted systemunder which collaboration among aerial nodes, ground stations, and edge servers is essential for enhancing the sustainability of the network. Trust-aware systems catch the malicious and faulty nodes, avoid false propagation of data and increase trust with available trustworthy decision. But being trust-based, it keeps the social relationships by incurring more signaling and computational expenses showing a trade-off between trust robustness and energy efficiency.

Taken together, to realize secure, privacy-preserving, and trustworthy UAV operations needs overall schematical designs as concerns the security strength or/and energy consumption or/and system longevity cannot be treated in one-sided manner. The new sustainable UAV systems should have adaptive and lightweight security, and the trust management needs to be coupled with the energy-aware control and meet regulatory and ethical considerations to provide long-term, scalable green flight operations.

4. Novel Taxonomy of Sustainable Green UAV Research Studies

To provide better visualization of the proposed taxonomy also in an easy-to-understand and intuitive manner, Fig. 4 gives a schematic classification of green UAV research studies along six main axes. The figure shows how different factors including sustainability scope, green enabling technologies, Intelligence level, application domains and evaluation and validation methodologies/performance metrics/sustainability metrics are interrelated in a single framework. The fact that the taxonomy is a result of text analysis and visualisation, we were able to convey in a two-dimensional representation visually not only researcher, methodological issues are rare to come by or nonexistent.

4.1. Sustainability Scope

The recent studies on the development of natural green UAVs are mainly concentrated on energy and environmental sustainability, but gradually shift to lifecycle and operational sustainability. Battery-less and solar-powered UAVs present a promising solution for the realization of long-endurance, emissions free flying platforms, when considering the possibility of hybridizing lightweight structures, renewable energy production and energy aware controls. AI-enabled UAV systems also promote sustainability via maximal energy efficiency, coverage and operational safety in smart logistics and monitoring applications. At the same time, the developed data-driven battery modeling and degradation prediction enables predictive energy management and gives potential to prolong battery life for greener UAV operations and less environmental influence.

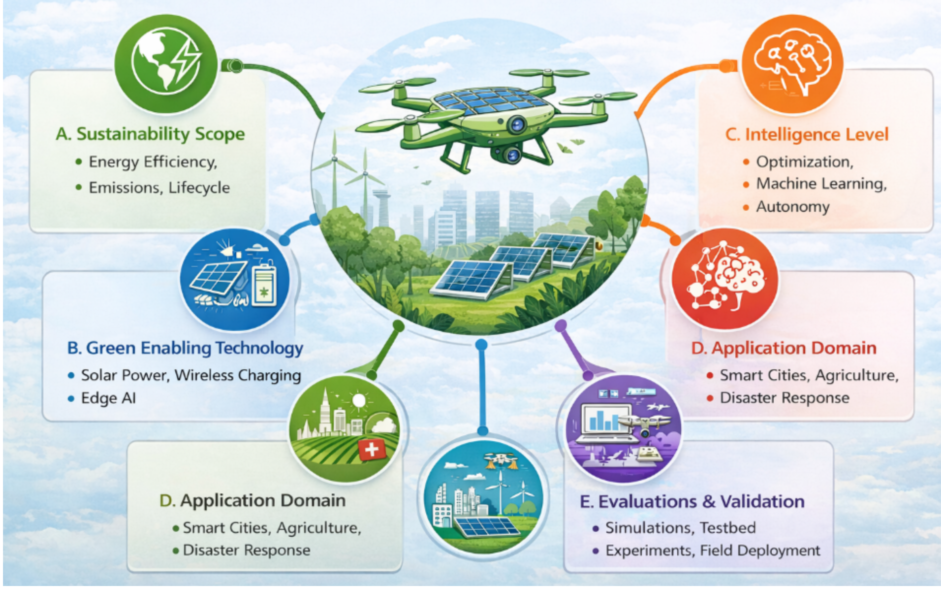

Fig. 4. Visual taxonomy of sustainable green UAV research studies across six dimensions

Liller et al. [74] studies a batteryless fixed-wing UAV that relies solely on solar power, providing design exploration, mechanical and electrical analysis as well as energy-aware control algorithms. Prototypes indoor and outdoor experiments display the feasibility of batteryless flight, maneuverability, and scalability to offer a sustainable solution for long-lasting UAV operations. Bibbo et al. [75] proposed a novel AI-driven sustainable UAV for urban logistics by leveraging solar-assisted energy supply, edge intelligence and structural health assessment. Experimental and field studies show a significant improvement in energy consumption, coverage rate, operating safety against disturbances and pollutant emission reduction which make the platform a viable approach for intelligent last-mile delivery. Al-Haddad et al. [76] examined UAV battery energy consumption and degradation based on a deep neural network trained with multiple DJI Mini 2 flight data. The resulting experimental results reveal high prediction accuracy and the obtained insights could be useful for predictive energy management, battery life extension, and greener UAV flight operations.

4.2. Green Enabling Technology

Sustainable UAV systems rely on green enabling technologies. Recent work combines solar power generation, energy-optimal trajectory planning and wireless charging to mitigate the consumption of propulsive forces and the associated carbon footprint. Advanced optimization algorithms combine considerations of flight dynamics, communication efficiency and atmospheric effects in order to maximize energy consumption. Further, the integration of edge computing, 6G communications and dynamic wireless charging supports scalable, cost-efficient UAV operations over urban and environment applications. Combined, these technologies turn UAVs from limited-range (due to power) platforms into agile, eco-friendly sky systems.

Abou et al. [77] considered an energy-aware UAV communication system with solar energy harvesting and trajectory optimization. A convex optimization formulated solution is further developed to minimize the propulsion energy consumption and improve communication efficiency, saving of carbon-footprint; numerical results show that our proposed sustainable UAV operation scheme is practically effective. Shaikh et al. [78] proposed an integrated UAV system with dynamic wireless charging plus intelligent edge computing and 6G communication.

The simulation demonstrates high charging efficiency, fast waiting time with cost and energy efficient process that scales up to improve UAV operation effectively for urban and environmental operations. Li et al. [79] introduced a general and flexible trajectory and velocity control framework to solve the energy-efficient UAV visual coverage problem. By jointly minimizing the altitude, visit order and intra/inter region path with SA, TSP and dynamic programming computation results prove its advantages in terms of significant reduction in energy consumption while providing superiority over state-of-the-art methods. Liu et al. [80] studies 3D position optimization of a solar-powered UAV relay for hybrid RF–optical communications. Taking atmospheric distortions for energy harvesting and links into account, it is found that the optimal placement of the UAV depends on channel conditions significantly, which leads to a maximal end-to-end capacity in sensor–UAV–OGS networks.

4.3. Intelligence Level

The intelligence of sustainable UAV has shifted from static optimization to learnability and autonomy decision making. Heuristic and swarm algorithms based path planning aware of the energy makes it possible for UAV to collect data in large scale under harsh energy conditions. Newer works adopt deep learning and reinforcement learning to improve single- and multi-UAV systems on their autonomy, cooperation, and power efficiency. Multi-Agent Reinforcement Learning agents also lead to enhanced accuracy, coverage and energy efficiency performance of the tracking, emphasizing the importance of intelligence in sustainable UAV operations.

Shen et al. [81] addresses the problem of energy efficient UAV-assisted data collection for mMTC networks. Formulating the trajectory optimization with energy constraints, it presents clustered GOP- and PSO-based algorithms for scalable and energy-efficient trajectory design, which can outperform global optimal methods in large-scale or distributed MTCD. Almalaq et al. [82] presents an evolutionary deep learning model with genetic algorithms and LSTM to optimize hyperparameters and time-lag inputs for building energy prediction. Experiments on public datasets demonstrate higher accuracy in the short-term prediction compared with traditional and classical deep learning methods.

Bai et al. [83] presents a thorough tutorial on RL-based multi-UAV wireless networks, including the basics of RL theory, main application domains and recent advances. It outlines how RL can provide autonomy in decision-making, resource allocation and cooperation of devices when applied to MUWNs and pinpoints what open problems should be addressed in future intelligent MUWN research. Xia et al. [84] introduced an end-to-end cooperative multi-agent reinforcement learning architecture for UAV target tracking. With energy-aware transmission modeling and spatial entropy included, simulations demonstrate better tracking success rate, coverage and power efficiency as compared to deep reinforcement learning-based benchmarks.

4.4. Application Domain

Use cases of sustainable green UAVs have been demonstrated to various areas from smart to environmental applications. In smart cities, energy-efficiency UAV infrastructures need to be able to perform autonomous monitoring operations such as surveillance, traffic and urban sensing. Environmental applications include solar-powered drones to monitor real-time air quality and investigate smoke plumes. Energy-efficient clustering and UAV-based sensor networks optimize the network lifetime, decrease energy consumption in precision agriculture. Besides, as a critical role in disaster response and smart grid inspection, path and planing of UAVs can improve the feasibility and flexibility under constrained environment.

Jain et al. [85] introduced an energy-aware framework for self-autonomous UAV based smart city surveillance using computer vision and intelligent control. It also addresses some of the major challenges related to energy management, data security, and autonomy, along with future research trends in Internet of Drones–facilitated urban surveillance systems. Yadav et al. [86] introduced a solar-powered fixed-wing UAV for spatiotemporal air quality monitoring with low-cost sensors. Field tests demonstrate real-time data acquisition and reporting, that affords hyperlocal pollution mapping and hot-spot tracking in urban, industrial and smart-city scenarios. Paul et al. [87] suggested the energy-efficient clustering algorithm for UAV-based agricultural sensor networks.

Optimally selecting cluster head using energy, Antenna gain and distance makes simulation result of less energy consumption, prolonged network life time and enhanced QoS, proves it to be an effective solution for Precision Agriculture & Sustainable crop monitoring. Golam et al. [88] presented an UAV-based emergency communication system for disaster areas, taking into account energy limitation by ground recharging and path planning algorithm. Simulation results verify energy savings and better connectivity, which both improved the feasibilities for UAVs as temporary base stations in SRR scenarios. Zhou et al. [89] studied energy-efficient IIoUAV deployment for smart grid power line inspection. What's more, by co-designing high and low time-scale ops there and decomposing the NP-hard problem here for solve with dynamic programming, auction as well as matching theories, together with real simulations to prove promoted energy efficiency and practical possibility.

4.5. Evaluation & Validation Method

The latest sustainable UAV approaches rely on multi-level validation process in order to justify their claims. Mathematical modeling and simulations continue to be a popular tool for investigating energy consumption, trajectory planning, and deployment strategies. Nevertheless, there is an increasing focus on experimental testbeds and field deployments when it comes to real-world solar-powered sensing and perception systems. Our experimental results indicate trustworthy long-term operations, accurate sensing and reduced energy overhead, increasing the practical soundness of green UAV solutions from simulation-only validation.

Asim et al. [90] introduced a joint UAV trajectory and IRS passive beamforming optimization framework that minimizes both the energy consumption and task completion time. The proposed TPPBA-VP algorithm can successfully manage the complicated multi-variable problem, and excellent results are achieved through simulations outperforming other existing methods. Min and So [91] presented a novel low-cost deployment scheme in order to balance the trade-off between positioning and power by deploying multi-UAV based BSs such that the sum of positioning error is minimized. Simulations reveal that better convergence speed, stability and QoS can be achieved in the proposed approach based on hybrid ISA-PSO, as compared with other traditional deployment methods.

He et al. [92] proposed a novel three stage optimization framework for UAV perception and navigation intelligence using graph modeling, curvature based parallelization and energy aware many-core mapping. Experimental results indicate that the proposed method can reduce energy overhead, execution time and flying time for flight controlling, path planning and visual navigation tasks. Wei et al. [93] assessed a solar-charged air monitor system for mid-tier long-term urban sensing. Results show reliable, ozone measurements, reliable wireless operation and accurate pollution source identification are presented, illustrating the feasibility of the system for long-term maintenance-free air quality monitoring.

4.6. Performance & Sustainability Metrics

Performance analysis in the context of sustainable UAV research is based on a broad spectrum of energy, endurance, cost and environmental metrics. Indices of interest include fuel consumption for propulsion, flight time to climb time ratio, power prediction accuracy and aerodynamic efficiency. State-of-the-art co-design methods couple energy and aerodynamics optimization for increased solar-powered UAV endurance. Cost and lifecycle indicators are being evaluated through techno-economic and environmental analysis techniques, allowing to evaluate in different perspectives the SUAV sustainability within the smart city and environ ecosystem. Such metrics enable a quantitative benchmarking of green UAVs solutions and yield insight on sustainability trade-offs

Girlevicius et al. [94] focusesed on the solar power integration with small scale fixed wing UAV for improved endurance. Using simulations and prototype experiments, we discuss practical mechanical and electrical challenges and demonstrate that thin-film photovoltaics can be used in retrofit applications while monocrystalline cells are better suited for purpose-built solar UAVs. Manjarrez et al. [95] presented a fuzzy-based energy estimation framework for UAV mission planning. Using Takagi–Sugeno modeling, optimized clustering, and battery state estimation, experiments show accurate flight-time margin prediction with only 2% error, enhancing UAV operational safety. Di et al. [96] presented an innovative energy–aerodynamic co-design approach for the solar-powered micro air vehicles, by integrating optimal placement of solar panel with CFD-based aerodynamic analysis. Wind tunnel experiment and flight test results endorse enhanced endurance, aerodynamic efficiency, indicating feasibility of solar-cell powered MAV configuration.

Stahl et al. [97] presented a performance comparison of eleven fully electric fixed-wing VTOL UAVs through a multidisciplinary design and optimization process. It assesses performance and cost, while looking at options such as low-drag stopped-rotor storage systems, hybrid battery architectures to improve range, endurance and efficiency. Saxena et al. [98] presented a holistic energy-aware framework for edge-intelligent drones, combining empirical energy modeling, sensing accuracy analysis, and multi-drone scheduling. Results show highly accurate energy prediction, significant reductions in energy use and mission time, improved robustness, and validation through a real-world people-counting case study. Yuekuan Zhou [99] investigated UAV-based Substrates at low altitudes from the perspective of lifecycle techno-economic and environmental analysis. It reviews UAV designs, power sources and smart city applications with a focus on carbon footprint tradeoffs and sustainability opportunities, as well as policy considerations for UAV deployment in future sustainable urban ecosystems.

5. Strengths and Limitations of Existing Sustainable Green UAV Studies

This section presents a critical overview of the advantages and limitations in the literature that can be found in sustainable green UAV research. Trends, benefits & challenges are identified by reviewing representative works across the dimensions of the proposed taxonomy. Table 2 provides a summary of these findings in terms of the identified major strengths and limitations for the sustainability scope, enabling technologies, intelligence level, application domains, evaluation methods and performance metrics. This comparative study provides an integrated overview about the state-of-the-art and can be used to detect knowledge gaps to trigger further research.

6. Results and Discussion

This section presents the analytical results based on taxonomic classification of the reviewed literature and their implications for green uav sustainable research. Instead of the descriptive summaries of each study, the discussion is a broader aggregation of trends, comparisons and absences across the dimensions in the taxonomy that have been identified.

6.1. Sustainability Scope and Green Design Trends

The analysis reveals that sustainability in contemporary UAV research is mostly framed with the respect to design aspects of operational—energy efficiency. About 70-75% of the surveyed papers are dealing with minimizing or extending flight duration for propulsion energy consumption as well as energy-aware trajectory design. Some of the researched enhancements to endurance and ground-based charging infrastructure minimization are solar-assisted propulsion and hybrid power architectures.

Table 2. Strengths and limitations of existing sustainable green UAV research studies across taxonomy dimensions

Taxonomy Dimension	Common Strengths	Common Limitations
Sustainability Scope (A)	Strong emphasis on operational energy efficiency through solar-powered, batteryless, and hybrid UAV designs.	Limited consideration of full lifecycle sustainability, including manufacturing impact, battery recycling, and end-of-life disposal.
Green Enabling Technology (B)	Effective integration of energy-aware trajectory planning, renewable energy harvesting.	Most solutions rely on idealized assumptions such as perfect weather conditions, and stable communication links.
Intelligence Level (C)	Advanced optimization, machine learning, and reinforcement learning enable adaptive, and autonomous.	Learning-based approaches introduce additional computational and communication overhead.
Application Domain (D)	Wide applicability across smart cities, environmental monitoring, precision agriculture, disaster response, and smart grid inspection demonstrates the versatility and societal relevance of green UAV systems.	Most studies focus on single-domain scenarios, with limited investigation of cross-domain interoperability and long-term deployment sustainability under heterogeneous operational conditions.
Evaluation & Validation (E)	Growing use of experimental testbeds, prototypes, and field deployments enhances practical credibility beyond simulation-based studies, especially for solar-powered sensing systems.	Simulation-based evaluation still dominates, and large-scale, long-term real-world experiments remain scarce due to cost, regulatory, and logistical constraints.
Performance & Sustainability Metrics (F)	Comprehensive reporting of energy consumption, endurance, latency, and cost metrics enables quantitative assessment of green UAV performance.	Lack of standardized benchmarking frameworks and unified sustainability indicators (e.g., carbon footprint, lifecycle cost) hinders fair comparison across studies.

On the other hand, full lifecycle sustainability (e.g., manufacturing impact, battery degradation/recyclability, end-of-life) is less characterized and mentioned in only $<20\%$ of reviewed works. This disparity precludes sustainable environmental gains to be derived from prospective solutions and justifies the development of lifecycle attitude in operational sustainability frameworks for aircraft, beyond flight-time optimisation.

6.2. Green Enabling Technologies and Intelligence Level

Technologically, the results evidence a clear trend into *smart and adaptive UAV systems*. AI-based methods, such as machine learning and reinforcement learning, are being used for trajectory optimization, energy prediction and autonomous decision making. Over 60% of the recent literature makes use of intelligent optimization techniques to improve UAV autonomy and operational efficiency.

Nevertheless, the embedding of intelligence causes still many computation and energy overhead. There are few works that directly consider the intelligence versus energy consumption trade-off, especially for resource-limited UAV platforms. This compromise is a crucial design consideration for the sustainable operation of UAVs, especially in long-endurance missions and large-scale applications.

6.3. Application Scenerios and Practical Implementation Considerations

Taxonomy-based results indicate the wide applicability coverage where smart city monitoring, environmental sensing, precision agriculture and disaster management are the most tackled application areas. These two application domains represent the focus of most research, since they are well aligned with sustainability goals and are socially relevant.

However, most investigations are application-dependent and concentrate on single deployment scenarios. There are few discussions or considerations given to cross domain interoperability and long-term operation under diverse environmental conditions and operational requirements. This limited practical scalability of so many proposed solutions highlights the fact, that flexible UAV architectures able to support multiple applications with very different sustainability requirements are required.

6.4. Evaluation Practices and Performance Metrics

In evaluation matters, energy efficiency and flight time are the most reported performances (extracted from 79.2% of the paper reviewed). Latency and throughput metrics Statistics on the communication in terms of latency or throughput are present in 40% of papers. Security, privacy and trust metrics is explicitly assessed in less than 25% of the study.

Furthermore, simulations based evaluation is the majority of what we know today with limited experimental testbeds and long-term real world deployments. Overall, the lack of established standards and sustainability performance indicators has caused a lack of comparable benchmarks across studies, which hinders cumulative advances in sustainable UAV research.

6.5. Strengths, Limitations, and Comparative Insights

Most importantly, the surveyed research work shows that there would be substantial innovation on energy-efficient design of UAVs, intelligent control and application dependent deployment. This taxonomy discusses these strengths and recurring weaknesses, such as the over-focus on operational efficiency, inadequate sustainability analysis through the life cycle futures by security considerations scatter evaluation methods.

In contrast with purely energy or communication-oriented studies in UAV literature, this paper delivers a comprehensive sustainability-focused study that allows the ability to examine and compare across categories and strategic insight to be formulated. The findings highlight that fully sustainable UAV systems can only be achieved by considering in an integrated manner energy, intelligence, security, lifecycle impact and application scalability rather than optimizing one of the above factors in isolation.

6.6. Discussion Summary and Research Implications

The results show that although significant progress has been made towards green and smart UAV systems, the research is still fragmented. Filling these gaps will call for standardized assessment practices, lightweight and energy aware intelligent models, lifecycle-oriented design methodologies, and stronger bonding between sustainability issues and deployment constraints. This intuition is the direct motivation for the open challenges and future research directions outlined in the next section.

7. Open Problems and Future Research

Although there has been much advancement in green UAV research, many open problems continue to exist which need to be resolved for enabling eco-friendly large-scale and long-term UAV implementations. The section presents open research challenges, as well as promising future directions that leverage the proposed taxonomy together with the investigation into existing studies.

- Energy Limitations and Long-Endurance Operation: Even if UAV endurance has been significantly enhanced using energy harvesting and energy-aware control methods, onboard energy remains the basic constraint. There need to be more studies related to the advanced hybrid power systems, better battery technologies and adaptive energy harvesting models that work well for unstable environments such as unpredictable weather and illumination.
- Lifecycle Sustainability and Environmental Impact: Most existing body of research focuses on operational energy efficiency, whilst full lifecycle sustainability is neglected. Future studies

should integrate LCA methodologies including but not limited to, manufacturing processes and material selection, battery aging scenarios (e.g., repeated recharge/discharge cycles), recyclability and end-of-life treatment. Techno-economic and environmental analyses can be systematically combined to provide an integrated sustainability assessment of UAV systems.

- Accommodation of Multi-UAVs/Swarm Systems: Scalability of sustainable solutions for UAV remains a problem – particularly in dense multi-UAVs and swarm deployments. A coordinated energy-aware communication, distributed intelligence and lightweight cooperation mechanisms are necessary to lessen the signaling overhead and avoid congestion. Decentralized control and learning methods that scale well should be examined further that do not harm energy efficiency.
- Lightweight Intelligence and Energy-Aware AI: Although AI-empowered UAVs can bring autonomy and flexibility, learning-based models also impose extra computation/energy cost. Future AI studies should focus on producing light-weight, interpretable and energy aware AI models while trading-off learning accuracy with power efficiency. Model compression, federated learning and edge-assisted intelligence are promising frameworks toward sustainable UAV intelligence.
- SPT under Energy Constraints: The three mechanisms i.e., security, privacy and trust are still closely related to energy consumption in the UAV systems. Developing sustainable and thin security solutions concentrating on sufficient protection is a challenging open issue. Future directions Future works should consider the integrated optimisation of security strength, trust management and energy consumption, especially in multi-UAV and UAV-assisted edge networks.
- Standardized Benchmarking and Evaluation Frameworks: The absence of standardized benchmarking criteria and sustainability indicators prevents a fair comparison between cases. One direction for future research is to develop standardised testing and evaluation protocols covering conservation of energy, environmental impact, cost and performance under real-world operating conditions. Open access datasets, testbeds and reproducible experimental procedures will be essential to achieve this aim.
- Regulatory, Ethical, and Social Considerations: In addition to technical issues, a long-term deployment of UAVs needs to tackle the legal and social acceptance aspects. In the future, it might be necessary to take airspace regulations, privacy protection, noise pollution and also social impact into account for designing green UAV system. In this regard, it is believed that coordinated action by the research community, the policy makers and the industry involved in UAV operation will be essential to guarantee a responsible and sustainable integration of UAVs in smart environments.

Overall, solving these open issues calls for an interdisciplinary investigation that collectively integrates the energy efficiency, intelligence, security, lifecycle sustainability and societal impact. Pushing these directions will be critical in the realization of sustainable green UAV systems for future smart and environmental applications.

8. Conclusion and Future Work

In this article, a detailed review has been developed on recent systematized sustainable green UAV for smart and environmental-oriented applications. The review examines representative studies based on sustainability scope, enabling technologies, intelligence level, application domains used to integrate IoT technology, and evaluation practice in different performance metrics that mutually constituting a comprehensive vision for potential design principles and future research directions. The review also suggests that previous work mostly focused on operational energy efficiency, using renewable energy harvesting and optimizing UAV trajectory with the awareness of energy consumption/efficiency as well as AI for optimization in order to increase the enduranceness and autonomy of a UAV. Although these methods have resulted in significant advancements, that is advantageous and useful, important aspects, such as full lifecycle sustainability, security guarantees for very large scale objects, privacy and trustyes care operation of those components have not been fully supported. And on the other hand, without a series of benchmarking platform and long term real-world validation data, it is difficult to make fair comparison among these algorithms and easy to push these methods into practice.

The implications of the findings from a strategic viewpoint are that truly sustainable UAV systems can only be realized by transitioning from isolated performance optimization to holistic design methodologies integrating energy efficiency, intelligence, security, life cycle impact and application scaling. Light and energy-efficient AI models, lifecycle-based sustainability assessment, and integrated evaluation standards are identified as the main themes for future research. This study is not without limitations that are common to narrative reviews, namely potential publication bias and the use of particular databases and representative studies. However the taxonomy is a flexible and expandable one and it can be further refined based on future research.

In conclusion, this review brings the fragmented research efforts together to establish a sustainable direction by proposing a systematic and consolidated sustainability-related framework for the proponents of future work for all research aimed at scalable, intelligent and environmentally-friendly UAV systems for next-generation smart and environmental applications.

Author Contribution: All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

Funding: This research received no external funding

Acknowledgment: This work was supported by the Deanship of Scientific Research, Vice Presidency for Graduate Studies and Scientific Research, King Faisal University, Saudi Arabia (Grant No. KFU260301).

Conflicts of Interest: The authors declare that they have no conflict of interest.

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