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Research Article

Hydrogen-powered UAVs: A systematic review of technological advancements, safety frameworks, and future prospects

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ABSTRACT

Hydrogen aviation stands out as a crucial avenue for achieving deep decarbonization; however, its commercial adoption is currently hindered by substantial logistical and economic challenges. In this context, unmanned aerial vehicles (UAVs) emerge as a promising initial market for hydrogen propulsion, leveraging the technology's high gravimetric energy density and the comparatively lower barriers to certification that align well with UAV operational requirements. This study conducts a comprehensive review of the research and development landscape for hydrogen-powered UAVs, examining their application potential, key technological advancements, lifecycle carbon reduction capabilities, and safety considerations. The findings indicate that hydrogen-powered UAVs are particularly well-suited for applications in power line inspection, logistics and distribution, and agriculture, primarily owing to their extended endurance and ability to operate across a wide temperature range. Additionally, the zero-carbon operation of these UAVs underscores their significant carbon reduction potential from a lifecycle assessment viewpoint. Importantly, safety considerations for hydrogen-powered UAVs necessitate a systematic approach that addresses three critical dimensions: design requirements, hydrogen storage and refueling protocols, and adherence to regulations, codes, and standards (RCSs). While hydrogen-powered UAVs exhibit vast development potential and promise substantial reductions in carbon emissions, collaborative engagement among diverse stakeholders will be essential to propel technological innovation, enhance infrastructure development, and support favorable policy frameworks.

1. Introduction

Hydrogen-powered unmanned aerial vehicles (UAVs) have rapidly evolved from experimental models to operational systems and now stand as the most realistic entry point for hydrogen aviation (Shen et al., 2024). Fuel-cell propulsion provides endurance that is typically three to ten times longer than lithium-ion batteries, allowing missions that last hours instead of minutes (He et al., 2026). This combination of high gravimetric energy density, quick refueling, quiet operation, and low thermal signature makes hydrogen UAVs highly effective for applications such as surveillance, reconnaissance, logistics delivery, mapping, and infrastructure inspection (Rostami et al., 2025). The smaller size of UAVs, flexible certification frameworks, and early commercial adoption create favorable conditions for hydrogen integration compared with crewed aircraft. As a result, UAVs serve as practical technology testbeds, generating design data, operational knowledge, and refueling solutions that will inform the future of hydrogen-powered aviation.

Because of the immense potential of hydrogen in aviation sector, the fuel has become a key focus in global energy strategies and aviation decarbonization pathways. At the policy level, China released the *Green Aviation Manufacturing Development Outline* (2023 to 2035) in 2023 to define priority directions for research and development of hydrogen aviation technologies, promote demonstration activities involving hydrogen-powered aircraft, and initiate work on relevant standardization systems (Ministry of Industry and Information Technology of the People's Republic of China et al., 2023). In 2023, the Clean Aviation initiative of the European Union identified hydrogen-powered regional aircraft as a major research priority, with commercial introduction targeted for 2035 (Clean Aviation Joint Undertaking, 2023). In 2024, the Federal Aviation Administration of the United States (FAA) released

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the Hydrogen-Fueled Aircraft Safety and Certification Roadmap to present a structured framework for safety certification and technology development of hydrogen-powered aircraft. Such policy frameworks strengthen the overall foundation for advancing hydrogen technologies in aviation, including UAV applications (Federal Aviation Administration, 2024).

In parallel, the rapid development of the low-altitude economy has created new opportunities for hydrogen-powered UAV applications. In China, the low-altitude economy was officially identified as a strategic emerging industry in *the 2024 Government Work Report* (State Council of the People's Republic of China, 2024), and has continued to receive strong policy support in subsequent national development planning. The expansion of low-altitude application scenarios, including logistics distribution, infrastructure inspection, emergency response, and aerial monitoring, is expected to significantly increase the demand for long-endurance and low-carbon UAV platforms (Zhou, 2025). Hydrogen-powered UAVs are considered a promising technological pathway for supporting the sustainable development of the low-altitude economy.

Supportive policies and technological breakthroughs have significantly accelerated the development and commercialization of hydrogen-powered UAVs. Evidence from global industry landscape demonstrates the rapid expansion of hydrogen-powered UAV development. According to QYResearch survey data, the global hydrogen-powered UAV market was valued at $219 million in 2024 and is projected to reach $1.161 billion by 2031, with an expected compound annual growth rate (CAGR) of 29.6% during the stated period (QYResearch, 2025). China has invested significantly in the development and testing of hydrogen-powered UAVs. Forecasts by Kaiyuan Securities indicate that the commercialization of hydrogen-powered UAVs in China is expected to progress into an early-stage phase between 2025 and 2030, and the national market size is projected to reach 14.13 billion yuan by 2030 (Kaiyuan Securities, 2025). However, it should be noted that these market forecasts are inherently subject to uncertainties associated with policy implementation, hydrogen infrastructure deployment, technology cost reduction, certification progress, and market acceptance. Therefore, although these forecasts and commercialization timelines provide useful references for understanding future industry trends, they should still be interpreted with appropriate caution. Multiple companies worldwide have launched high-performance hydrogen-powered UAV products. Heven Drones in Israel has developed several long-endurance, hydrogen-powered platforms with vertical takeoff and landing (VTOL) capability, strengthening military collaborations in recent years (Wrobel, 2025). The hydrogen-powered hybrid Raybird UAV, developed by the Ukrainian company Skyeton, has been deployed in actual combat since 2025 (Skyeton, 2026a), marking the first clear case of applying hydrogen propulsion systems in real-world combat scenarios. Doosan Mobility Innovation (DMI) in South Korea has achieved mass production and commercialized hydrogen fuel cell UAVs, providing multi-hour flight duration for industrial inspection applications. HiTS Hydrogen Power Technology is promoting large-scale development and production of hydrogen-powered UAVs in the Chinese market and simultaneously expanding overseas assembly and sales. Representative commercial hydrogen-powered UAV platforms are summarized in Table 1.

Despite these developments, hydrogen-powered UAVs still face several technical and safety challenges. The extremely low density of hydrogen at standard temperature and pressure poses challenges for onboard hydrogen storage systems (Massaro et al., 2023). Current hydrogen fuel cells suffer from limited power density and slow dynamic response (Tak et al., 2026). The flammable and explosive nature of hydrogen makes safety a particularly critical concern for hydrogen-powered UAVs (Anekwe et al., 2025). Therefore, integrating hydrogen systems into UAV platforms requires rigorous safety design and strict management protocols.

This paper presents a systematic review of the current status and future prospects of hydrogen-powered UAVs, covering application suitability, key technological advances, life-cycle carbon reduction capabilities, and safety considerations. Based on this review, the discussion highlights barriers in hydrogen storage, fuel cell performance, and system-level safety design to identify approaches to overcome these technical limitations.

2. Background on hydrogen-powered aviation

2.1. Development of hydrogen propulsion in aviation

The application of hydrogen propulsion in aviation dates back to 1972, when Lockheed-California Company explored the potential of using liquid hydrogen (LH_2) to power aircraft (Brewer, 1976), laying early groundwork for hydrogen propulsion research. In 1988, the Soviet Union completed a 21-min test flight using a modified Tu-155 passenger aircraft, with one engine running entirely on LH_2 throughout (Sosounov and Orlov, 1990), demonstrating the technical feasibility of cryogenic hydrogen in aviation propulsion. In the 21st century, as concerns about climate change intensified, hydrogen aviation technology entered a new phase of development. In 2008, a modified Diamond DA20 aircraft completed a first flight powered by a hydrogen fuel cell in a development program led by Boeing (Smykla et al., 2021). In 2016, the DLR Institute of Engineering Thermodynamics in Germany conducted the world's first test flight of a four-seat hydrogen fuel cell aircraft, the HY4,

Table 1
Representative commercial hydrogen-Powered UAV platforms.

Manufacturer	Country	Model	Platform type	Power (W)	MTOW (kg)	Payload (kg)	Endurance (min)	Refs
Doosan Mobility Innovation Co., Ltd.	South Korea	DS30W	Multirotor	2700	24.9	3	120	DOOSAN (2019)
JOUAV Co., Ltd.	China	CW-25H	VTOL fixed-wing	~1250	31	4	330	JOUAV UAS (2022)
Heven Drones Ltd.	Israel/USA	H2D55	VTOL multirotor	N/A	29	4.5	120	Heven Drones (2023)
H^3Dynamics Holdings Pte. Ltd.	Singapore/ France	HYWINGS	Fixed-wing	200	7	N/A	600	H3 Dynamics (2016)
Skyeton LLC	Ukraine	Raybird (hydrogen-hybrid)	Fixed-wing	N/A	23	5-10	~720	Skyeton (2026b)
HiTS Hydrogen Power Technology Co., Ltd.	China	Atlas H100	Multirotor	14000	100	60	>180	HiTS (2022)
Cellen H_2, Inc.	USA	H2-6	Multirotor	2400	21	2.7	150	Cellen (2025)
Skycutter UAS Ltd.	UK	Gryphon	Multirotor	N/A	25	6	~180	Skycutter (2025)

Note: "MTOW" denotes maximum take-off weight. "~" indicates approximate values derived from manufacturer specifications or public demonstrations. "N/A" denotes that the parameter has not been disclosed by the manufacturer. Specifications are sourced from manufacturer websites and public literature at the time of access. Manufacturer updates may occur; please refer to official sources for the latest data.

further advancing the use of hydrogen in small aircraft (DLR, 2016). In 2020, Airbus launched the ZEROe program, introducing four hydrogen-powered commercial aircraft concepts and focusing on the development of hydrogen fuel cell turbofan aircraft (Airbus, 2020). However, commercialization of hydrogen-powered passenger aircraft remains hindered by stringent requirements for technological maturity and safety in large airliners. In 2024, Airbus announced a delayed timeline for the ZEROe project, reflecting the complexity of these technologies (Perry, 2025). In contrast, UAVs offer advantages such as relatively simple system architectures, no need for crew accommodation, and flexible allocation of space for hydrogen storage, making them an ideal entry point for the deployment of hydrogen aviation technologies.

2.2. Hydrogen-powered UAVs: progress and advantages

Research on hydrogen-powered UAVs has intensified over the past decade, driven by advances in fuel cell efficiency, lightweight hydrogen storage, and power management systems. Since the early 2000s, multiple hydrogen-powered UAV prototypes have undertaken test flights, demonstrating progressively longer endurance and higher payload capacities.

Current mainstream UAVs can be categorized into three major types based on aerodynamic layout: fixed-wing, rotary-wing, and hybrid-wing (Darvishpoor et al., 2020; Lee et al., 2021; Rojo-Rodriguez et al., 2024), as shown in Fig. 1. Fixed-wing UAVs resemble general-purpose aircraft and use wings to generate lift. They feature extended endurance, high flight speeds, and high payload capacity. These UAVs are suitable for tasks such as large-area surveying and long-distance inspection missions, but their takeoff and landing require runways or catapult systems, which constrains operational flexibility (Darvishpoor et al., 2020). Rotary-wing UAVs rely on multiple rotors for lift, enabling vertical takeoff, landing, and hovering with high maneuverability. They excel in complex scenarios such as aerial monitoring and emergency rescue. However, rotary-wing UAVs have lower aerodynamic efficiency, more complicated structures, and limited payload capacity (Rojo-Rodriguez et al., 2024). Hybrid-wing UAVs integrate propellers onto a fixed-wing airframe, combining the cruise efficiency of fixed-wing aircraft with the vertical takeoff and landing capability of rotary-wing systems (Darvishpoor et al., 2020). Hybrid-wing UAVs overcome terrain limitations, expanding their application scenarios. Early hydrogen-powered UAVs were primarily fixed-wing aircraft, predominantly deployed in military applications. In recent years, the growing deployment of UAVs in civilian domains has driven rapid development of rotary-wing and hybrid-wing platforms powered by hydrogen. Primary propulsion approaches for hydrogen-powered UAVs include hydrogen gas turbines and hydrogen fuel cells; some architectures also incorporate lithium batteries as auxiliary energy storage to support peak power demands, with specific configurations detailed in Chapter 4. Hydrogen-powered UAVs can be configured with any of these three power sources based on specific design requirements. Representative examples are summarized in Table 2. Early hydrogen-powered UAVs predominately featured large fixed-wing airframes powered by hydrogen internal combustion engines or high-power fuel cells, and were mainly used in long-endurance, high-altitude, or scientific research missions. With ongoing advances in fuel cell technology and growing diversity in operational requirements, hydrogen-powered UAVs have progressively adopted miniaturized and lightweight designs. This trend has facilitated the development of fuel cell-powered rotary-wing and hybrid-wing platforms, which offer greater mission flexibility and broader applicability.

Hydrogen-powered UAVs have longer flight endurance and faster refueling than lithium-battery and hybrid gasoline-battery UAVs. Key performance metrics for these platforms are summarized in Table 3. Hydrogen-powered systems use hydrogen as an energy carrier and deliver substantially higher gravimetric energy density than lithium-battery systems. At the system level the specific energy of fuel cell systems typically ranges from 300 to 1000 Wh/kg, far exceeding that of state-of-the-art lithium batteries which provide 150 to 250 Wh/kg (PW Consulting ChemicalEnergy Research Center, 2025). This higher specific energy enables hydrogen-powered UAVs to achieve longer endurance compared to battery-powered UAVs with the same takeoff weight. High pressure gaseous hydrogen storage at 35 to 70 MPa can be replenished in 3 to 5 min. In contrast, recharging lithium batteries is much slower, which typically requires 30 min to several hours depending on the charging infrastructure. Hydrogen-powered UAVs operate reliably across a temperature range from −40 to 60°C (Arat and Albayrak Çeper, 2025). In contrast low temperatures cause significant performance degradation in lithium batteries which restricts their operation in extreme environments. Compared with hybrid gasoline-battery UAVs hydrogen-powered UAVs sustain long endurance and high payload capacity while producing only water as exhaust. This results in no direct carbon emissions during operation. Conversely hybrid gasoline-battery UAVs produce greenhouse gas and pollutant emissions during operation (Zhou et al., 2026). They also generate significant noise and require more frequent maintenance.

However, hydrogen systems face practical constraints. Hydrogen infrastructure remains limited compared with the widespread availability of battery charging systems, and the overall system cost is generally higher due to storage, fuel cell stack, and balance-of-plant requirements. Consequently, these characteristics indicate a clear application-driven differentiation: battery-powered UAVs remain more suitable for short-duration, low-cost missions, whereas hydrogen-powered UAVs are better suited for long-endurance, high-payload, and special environmental scenarios.

3. Applications of hydrogen-powered UAVs in long-endurance missions

UAVs operate flexibly in complex environments owing to compact airframes and low takeoff mass. As the low-altitude economy industry continues to expand, UAVs have become a hotspot for cross-sectoral technological convergence and industrial innovation. UAVs serve a wide range of applications, with demand increasing rapidly across commercial, public service, and consumer entertainment sectors. At the same time, increasingly diverse application scenarios impose higher requirements on UAV performance, particularly in endurance, environmental adaptability, and payload capacity. Hydrogen-powered UAVs address key limitations of traditional lithium-battery and hybrid gasoline-battery UAVs, including limited flight time and direct carbon



Fig. 1. Three aerodynamic layout types of UAVs.

Table 2
Representative hydrogen-powered UAV models.

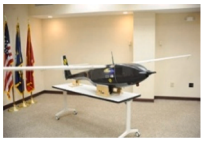
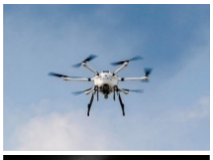
Year	Photo	Model	Configuration	Power style	Power (W)	Payload (kg)	MTOW (kg)	Endurance (min)	Refs
2009		Lon-Tiger	fixed-wing	FC	550	2.25	19	2880	Naval Technology (2013)
2010		Global Observer	fixed-wing	ICE/FC	N/A	N/A	1805	10080	Airforce Technology (2010)
2012		Phantom Eye	fixed-wing	ICE	111855 ×2	N/A	4241	240 - 480	Richardson (2012)
2012		Leap 1	fixed-wing	FC	1000	1	21	120	Xu (2012)
2016		Hywings	fixed-wing	FC	200	N/A	7	600	H3 Dynamics (2016)
2017		Jupiter-H2	rotary-wing	FC	650	1.25	5.2	120	Flightwave (2017)
2019		DS30w	rotary-wing	FC	2700	3	24.9	120	DOOSAN (2019)
2021		CW-25H	hybrid-wing	FC	1250	4	31	330	JOUAV UAS (2022)
2024		Tianmu mountain No.1	rotary-wing	FC	N/A	6	25	240	Tianmu Mountain Laboratory (2024)
2025		Raybird (hydrogen-hybrid)	fixed-wing	FC	N/A	5-10	23	~720	Skyeton (2026b)

Table 3
Comparison of UAVs with different power sources.

Power source	Typical product	Flight time (min)	MTOW (kg)	Payload (kg)	Energy replenishment time (min)	Features
Hydrogen FC	HydroCopter 4 (Hydrogen Craft Corporation, 2025)	150	24	5	~3-5	Long endurance, fast refueling, high cost, zero operational emissions, suitable for long-endurance missions
Battery	DJI Matrice 400 RTK (DJI, 2025)	59	15.8	6	45-110	Short endurance, slow charging, low cost, zero operational emissions, suitable for short-range missions
Gasoline	HC-332H (Honeycomb Aerospace, 2019a)	210	19.8	4	~5-10	Long endurance, fast refueling, moderate cost, significant emissions, suitable for heavy-load and extended missions

emissions. These advantages enable hydrogen-powered UAVs to show strong substitution potential and broad development prospects in applications including power grid inspection, logistics delivery, agricultural spraying, and surveying and exploration.

3.1. Power line inspection

With the continuous development of the power industry, the demand for transmission infrastructure continues to grow, and the coverage area of power networks continues to expand. This trend makes routine inspection and maintenance of power facilities particularly crucial. Traditional manual inspections involve substantial workloads and pose significant risks, especially in complex terrain or adverse weather conditions (Xiao and Yin, 2017). UAV-based inspection reduces dependence on weather and terrain and supports faster and safer operations. The application of hydrogen-powered UAVs in power line inspections is shown in Fig. 2. A UAV equipped with hydrogen fuel cells can operate for hours or longer, which supports inspection of long-distance transmission lines. This capability reduces the need for mid-flight returns to recharge and significantly improves inspection efficiency. Hydrogen-powered UAVs support rapid refueling, which shortens downtime and facilitates continuous operation. Hydrogen fuel cell systems maintain stable output at low temperatures, allowing reliable inspection in cold regions. Therefore, hydrogen-powered UAVs are increasingly deployed for power line inspection tasks (China Hydrogen Alliance, 2024; Tianmu Mountain Laboratory, 2024; Xie, 2021; Yan and Zhang, 2023).

3.2. Logistics and distribution

UAVs hold significant application potential in the logistics and delivery sector, as shown in Fig. 3, particularly for “last-mile” delivery. By bypassing ground traffic congestion, UAVs enable rapid and flexible delivery (Goodchild and Toy, 2018). UAVs are especially suitable for scenarios such as emergency supply delivery in remote areas and transport of medical emergency equipment (Khan et al., 2021). Compared with traditional manual delivery, UAV-based logistics reduce labor demand and transportation costs. Diverse delivery requirements impose higher demands on UAV payload capacity and flight endurance. Hydrogen-powered UAVs use hydrogen fuel cell systems with higher specific energy density to support short-range inter-city cargo transport, overcoming the limitations of lithium-battery UAVs in payload capacity and flight duration. Testing and pilot operations for hydrogen-powered UAV cargo delivery are currently underway (Easy H2 Power, 2025; HiTS, 2025; People’s Daily, 2025; Yang, 2024).

3.3. Agriculture

From precision agriculture to intelligent crop protection, UAV technology is rapidly expanding its applications in the agricultural sector (Mukherjee et al., 2019), as shown in Fig. 4. UAV-based pesticide spraying, seeding, and fertilization improve operational accuracy and reduce exposure of personnel and the environment to chemicals (Yang et al., 2021). UAVs can monitor farmland conditions and collect crop growth data using multispectral, hyperspectral, or infrared sensors, enabling further optimization of crop management (Su et al., 2018). Hydrogen-powered UAVs achieve extended flight durations, allowing coverage of larger agricultural areas and reducing the frequency of return flights for recharging, which improves overall operational efficiency. Owing to the high energy density of hydrogen fuel cells, such systems support a larger payload, which expands the operational scope of agricultural UAVs. As an example, in 2024, HiTS Hydrogen Power Technology Co., Ltd. signed a cooperation agreement with Shanghai Hytekocean Co., Ltd. to export 1000 hundred-kilogram-class hydrogen-powered agricultural UAVs, marking the initiation of large-scale commercialization (Jiangnan Emerging Industries Cluster, 2024).

4. Key technologies

Hydrogen-powered UAVs rely on two core technological components: the propulsion system and onboard hydrogen storage (Xiang et al., 2025). These systems determine flight endurance, payload capacity, and operational reliability.

4.1. Propulsion systems

Two primary approaches use hydrogen as the energy source for UAV propulsion, as shown in Fig. 5. One approach replaces conventional fuel with hydrogen in a gas turbine. Hydrogen combustion in the turbine generates thrust (Ihsan Shahid et al., 2024). Turbofan and turboprop engines using hydrogen deliver high specific power and are applied in large UAV platforms. However, hydrogen turbine integration increases system mass and complexity for civilian UAVs. Besides, nitrogen oxides (NO_x) form during high temperature hydrogen combustion and require mitigation (Ihsan Shahid et al., 2024). The other approach uses hydrogen fuel cell systems that convert chemical energy into electrical

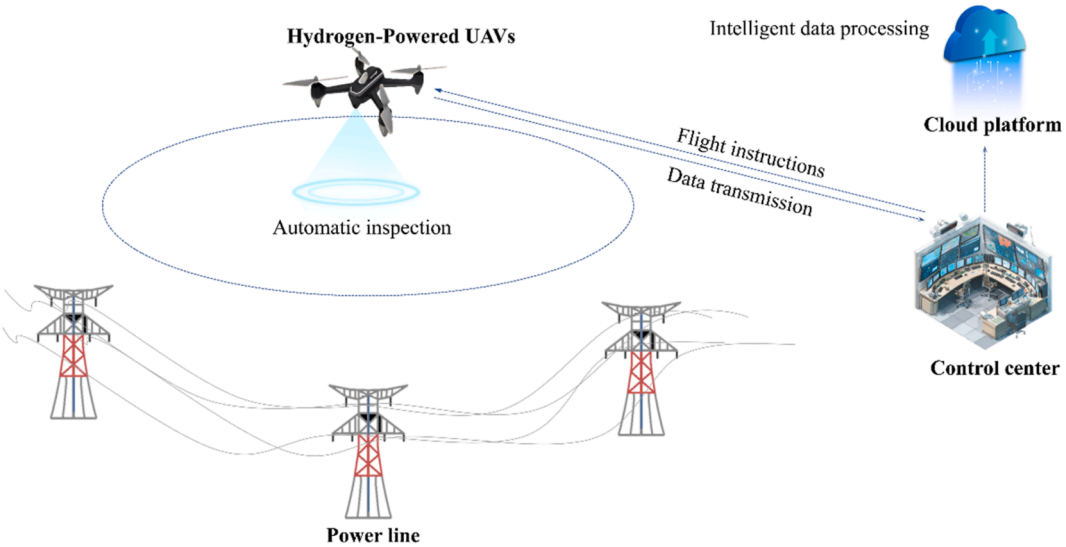


Fig. 2. Hydrogen-powered UAVs for power line inspection tasks.

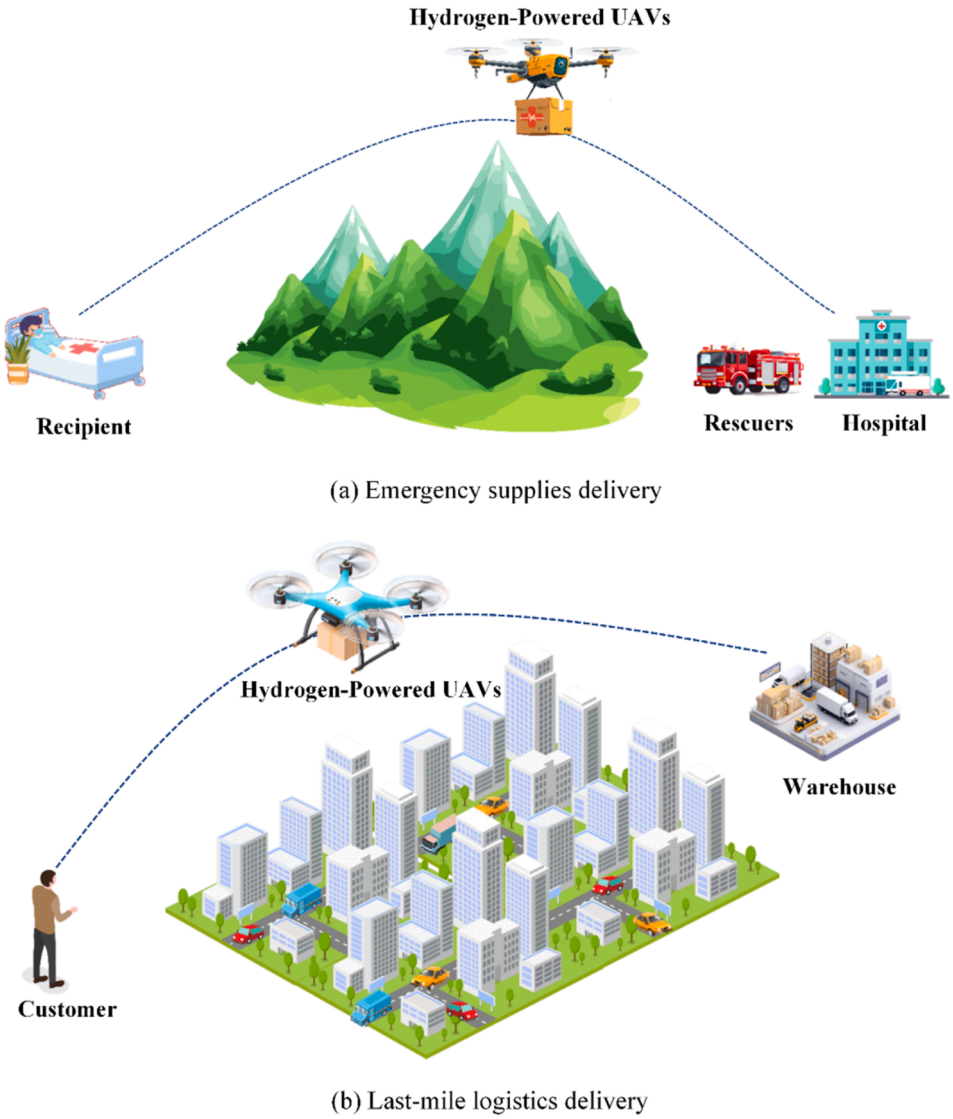


Fig. 3. Hydrogen-powered UAVs for logistics and distribution tasks.

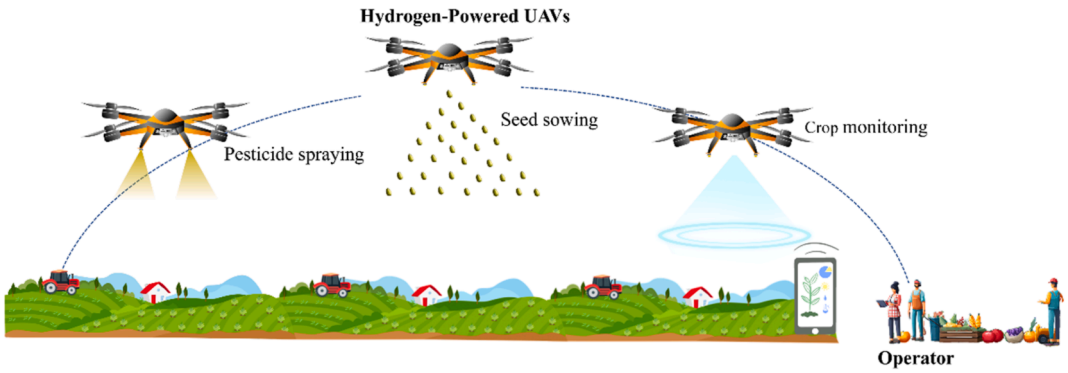


Fig. 4. Hydrogen-powered UAVs for agricultural tasks.

energy without combustion (İnci, 2022). Hydrogen fuel cell systems operate without emitting criteria pollutants, produce lower acoustic emissions than turbines, and achieve higher electrical efficiency. Hydrogen fuel cell systems are widely used in current hydrogen-powered UAVs. Moreover, hydrogen fuel cell systems can be effectively combined with other power sources, such as batteries, to compensate for their limitations in instantaneous power response (Lei et al., 2019), thereby providing more reliable power assurance for UAVs.

4.1.1. *Hydrogen fuel cells*

Polymer electrolyte membrane fuel cells (PEMFCs) are widely used in hydrogen-powered UAVs due to their rapid startup speed and high

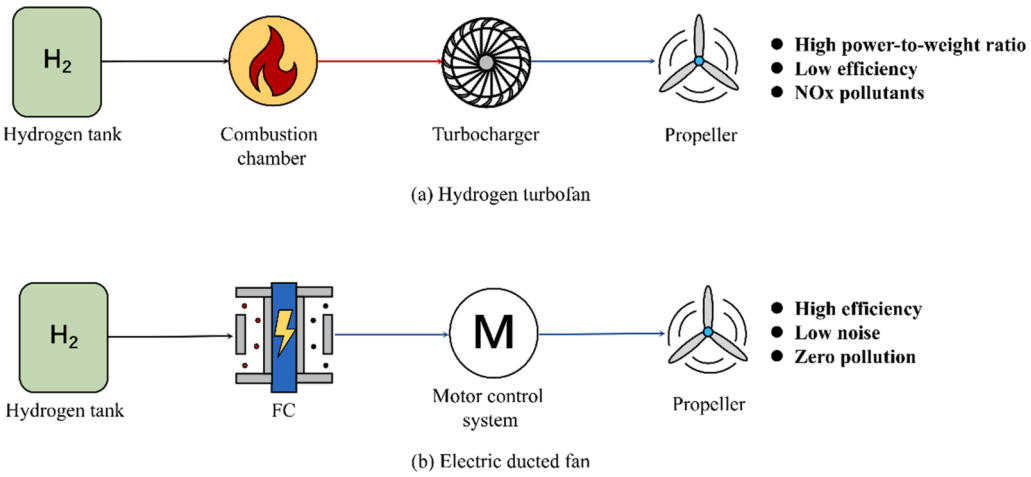


Fig. 5. Two hydrogen propulsion systems: hydrogen turbofan and electric ducted fan.

specific energy (Wen et al., 2011). A PEMFC uses a proton exchange membrane (PEM) coated with highly dispersed catalyst particles as the electrolyte. A single PEMFC cell mainly consists of a membrane electrode assembly (MEA), bipolar plates, and sealing gaskets. The MEA is formed by coating both sides of the PEM with a specific loading of platinum-based catalyst and a conductive porous gas diffusion layer. The basic principle of PEMFC operation is illustrated in Fig. 6. During operation, hydrogen enters the anode, diffuses through the gas diffusion layer, and is subsequently adsorbed by the catalyst, where an electrocatalytic reaction occurs. Hydrogen loses electrons to form protons (H^+). These protons traverse the PEM to reach the cathode, where they undergo a redox reaction with oxygen to produce water. Meanwhile, electrons flow through the external circuit via the load to the cathode, generating an electric current (Ozden et al., 2019). PEMFCs are regarded as a crucial component of future energy technologies. Recent studies have optimized PEMFC parameters such as catalyst loading, membrane thickness, and flow field design to improve power density and efficiency

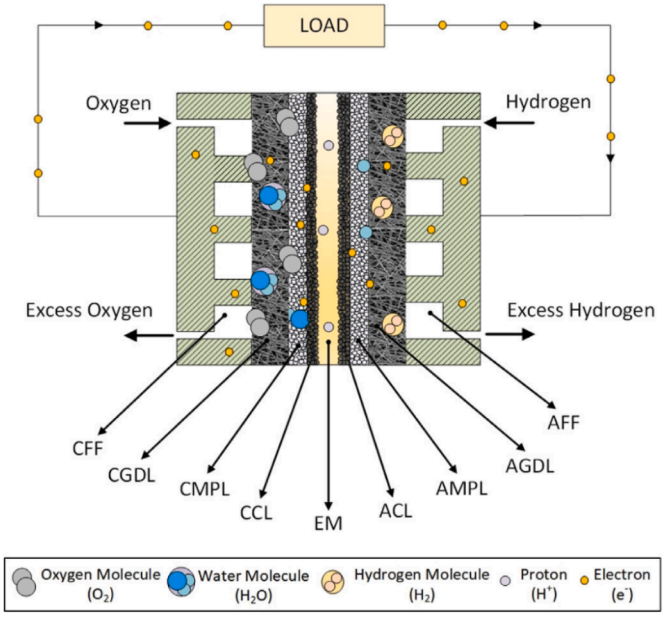


Fig. 6. Schematic of a PEMFC. CFF: cathode flow field; CGDL: cathode gas diffusion layer; CMPL: cathode microporous layer; CCL: cathode catalyst layer; EM: electrolyte membrane; ACL: anode catalyst layer; AMPL: anode microporous layer; AGDL: anode gas diffusion layer; AFF: anode flow field (Ozden et al., 2019).

(Hou et al., 2024; Madaan and Pandey, 2024; Madhavan et al., 2025; Thiele et al., 2024; Wang et al., 2023). PEMFCs have demonstrated promising adaptability across a wide range of operating temperatures and flight altitudes. Although low temperatures and reduced atmospheric pressure at high altitudes may adversely affect fuel cell performance, advances in thermal-water management and air-supply system design have significantly improved the operational stability of PEMFC systems under such conditions (Chen et al., 2024; Huang et al., 2024; Zeng et al., 2023). The continuous optimization and rapid technological advancement of PEMFCs provide the technical basis for their use as a reliable power source for UAVs (Dudek et al., 2013; Ferreira et al., 2024; Prajapati et al., 2023; Yin et al., 2024; Zeng et al., 2023).

4.1.2. *Hybrid propulsion system*

Fuel cells offer high energy density but deliver lower power density and respond slowly to transient load changes, limiting their ability to meet peak power demands during UAV takeoff or maneuvering (Kim and Kang, 2025). Combining fuel cells with secondary power sources to form a hybrid propulsion system provides a more effective solution. The high energy density of fuel cells supplies sustained baseline power during cruise flight, while other power sources deliver high-density power to meet peak power demands during takeoff or acceleration (Farajollahi et al., 2022). Therefore, this configuration improves energy utilization efficiency and power availability in hydrogen-powered UAV operations. Ng et al. (2021) demonstrated that a hybrid architecture combining hydrogen fuel cells and batteries can extend the flight duration of UAVs. Ustolin et al. (Ustolin and Taccani, 2018) showed that fuel cell-lithium battery hybrid systems are more suitable for long-range flights and have lower weight. Additionally, fuel cells can be integrated with solar cells to meet the requirements of different missions. Gadalla et al. (Gadalla and Zafar, 2016) integrated hydrogen fuel cells, photovoltaic cells, and batteries into a single system, using solar panels covering wing surfaces to provide an additional power source for small UAVs, further enhancing flight endurance.

4.2. *Hydrogen storage*

Hydrogen has a high gravimetric energy density (120 MJ/kg) but a low volumetric energy density of only 0.01 MJ/L at standard temperature and pressure. Therefore, hydrogen is typically stored as a compressed gas or as a cryogenic liquid to reduce the required storage volume. Safe, efficient, and lightweight hydrogen storage technology remains one of the core challenges limiting the development of hydrogen-powered UAVs. Ideal hydrogen storage technology for UAVs must provide both high gravimetric and volumetric energy density,

while also demonstrating fast reaction kinetics, high reversibility, reasonable cost, and strong safety.

4.2.1. High-pressure gaseous hydrogen storage

High-pressure gaseous hydrogen storage is currently the most technologically mature and widely used method, achieved by physically compressing hydrogen gas in storage tanks. The hydrogen storage capacity of a tank is quantified by the gravimetric efficiency, which is defined as the ratio of hydrogen storage mass to total mass (Adler and Martins, 2023). High gravimetric efficiency requires maximizing hydrogen storage mass or minimizing tank mass. When the hydrogen tank volume remains constant, increasing the hydrogen storage pressure provides a way to increase the stored hydrogen mass. Currently, common hydrogen storage pressures for UAVs are 350 and 700 bar. Another approach to improving weight efficiency involves reducing tank mass while maintaining safety and reliability. The development and application of composite materials have enabled lighter tanks, enhancing weight efficiency while offering higher reliability (Zhou et al., 2022). Currently, hydrogen-powered UAVs predominantly use carbon fiber-wound Type III and IV composite cylinders. Type III tanks feature an aluminum alloy inner liner, while Type IV tanks use a polymer inner liner. High-pressure gaseous hydrogen storage technology is the preferred solution for most hydrogen-fueled UAVs, as shown in Fig. 7, due to its high technological maturity, relatively low cost, and rapid refueling and discharge capability (Yanxing et al., 2019).

4.2.2. LH_2 storage

LH_2 storage involves liquifying hydrogen gas below −253°C (20 K). LH_2 can be stored at slightly higher than ambient pressure in specialized cryogenic insulated containers, providing an extremely high volumetric energy density of up to 70.8 kg/m^3 (Moradi and Groth, 2019), far exceeding that of compressed gaseous hydrogen at room temperature and typical UAV storage pressures. Research shows that UAVs equipped with LH_2 storage systems achieve up to 85% longer flight duration compared with systems using compressed gaseous hydrogen at the same total system mass (Stroman et al., 2014). The Meta Vista Corporation in South Korea reported a flight duration of 10 h and 50 min for a rotorcraft UAV using a LH_2 storage tank (Fuel Cells Bulletin, 2019).

Although LH_2 can significantly increase onboard hydrogen storage density, the technology involves high system complexity and cost. First, the hydrogen liquefaction process consumes a large share of the total energy required for hydrogen storage, accounting for approximately 30% (Liu et al., 2023). Additionally, maintaining cryogenic temperatures requires high-performance vacuum-insulated containers, such as those with multi-layer insulation (MLI), which further increase system cost and complexity (Li et al., 2022). As a result, LH_2 storage is primarily applied in medium-to-large hydrogen-powered UAVs or missions requiring exceptionally long flight durations, including scientific research and military operations. For small civilian hydrogen-powered UAVs, the added mass, cost, and thermal management demands of cryogenic systems often limit their practicality.

5. Carbon reduction potential

Carbon reduction potential of UAV-based delivery systems is determined not only by cleanliness of onboard energy sources, but also by endurance-related operational constraints and infrastructure requirements. Longer flight duration and extended operational range of hydrogen-powered UAVs can reduce infrastructure deployment and operational redundancy, and system-level carbon mitigation potential is greater.

Although hydrogen-powered UAVs generate no direct emissions during flight, their overall environmental performance depends strongly on upstream energy pathways and lifecycle processes. Evaluating the carbon reduction potential of these UAVs therefore requires a lifecycle-oriented analytical approach that extends beyond operational emissions alone. From this perspective, both the structural composition of lifecycle carbon emissions and the quantitative characteristics of these emissions for realistic energy supply conditions must be considered.

Accordingly, this chapter uses a two-level lifecycle assessment framework. At the first level, a cradle-to-cradle (C2C) framework is developed to conceptually identify carbon emission sources across the full lifecycle of hydrogen-powered UAVs. This full-lifecycle perspective is used for a qualitative analysis of the emission structure and sustainability implications of hydrogen-powered UAV technologies. At the second level, a well-to-wheel (WTW) method is applied for quantitative analysis, in which the assessment focuses on upstream energy carbon emissions and operational energy consumption, while manufacturing and end-of-life stages are excluded from numerical calculations due to data limitations.

5.1. Lifecycle carbon emission analysis

According to ISO standards, a lifecycle assessment encompasses raw material extraction, manufacturing, distribution, operation, maintenance, and recycling (Liu et al., 2024). For hydrogen-powered UAVs, the C2C carbon emission assessment framework integrates the low-altitude UAV carbon quantification method developed by Zhou et al. (Zhou, 2025) with the hydrogen energy lifecycle assessment method reported by Teng et al. (2023). The framework considers both the material and energy flows throughout the UAV lifecycle and holistically evaluate the environmental impacts by capturing emissions at each stage, as shown in Fig. 8.

5.1.1. Stage of production and distribution

The production stage involves structural material processing, component manufacturing for fuel cells and storage tanks, and the assembly of hydrogen-powered UAVs. The carbon emissions of this stage constitute a critical part of the total lifecycle emissions. Primary emission sources originate from the aluminum, copper, and platinum catalysts required in fuel cell manufacturing, as shown in Fig. 9. Emission reductions at this stage can be achieved through decarbonizing the electricity mix, optimizing metal procurement, and implementing corporate sustainability strategies (Xiong et al., 2025). Additionally,

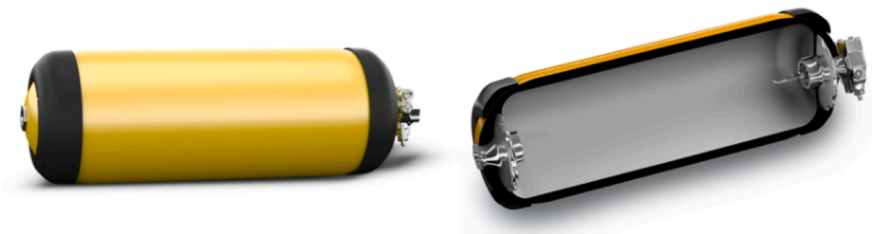


Fig. 7. Hydrogen tanks for the Toyota Mirai (Toyota Motor Corporation, 2014).

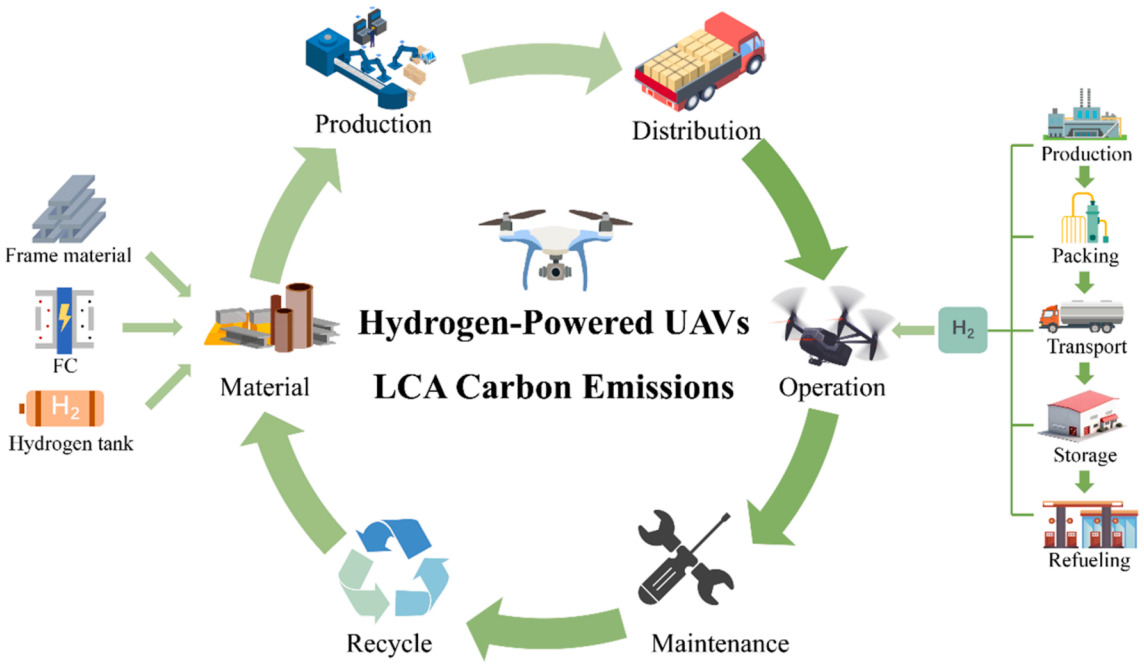


Fig. 8. C2C carbon emission assessment framework for hydrogen-powered UAVs.

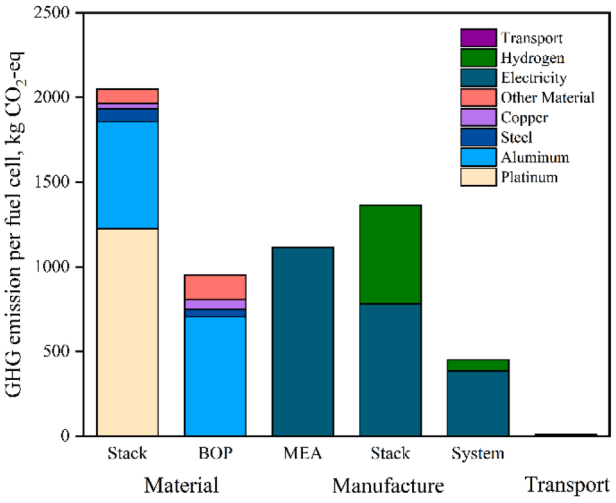


Fig. 9. Cradle-to-gate greenhouse gas emissions of the fuel cell (Xiong et al., 2025).

Type III and IV hydrogen storage tanks are typically used in UAVs, but the carbon fiber and composite materials used in such tanks are energy-intensive. For example, research shows that the hydrogen storage tanks contribute up to 38% of the global warming potential during the production phase of fuel cell vehicles (FCVs) (Benitez et al., 2021).

Following the production stage, the distribution of UAVs introduces additional emissions from transportation fuel consumption, logistics energy use, and associated infrastructure requirements. Although typically smaller than emissions from other stages, distribution contributes to the overall carbon footprint and should be accounted for in the LCA framework, particularly for large-scale UAV deployment (Bevilacqua et al., 2011)

5.1.2. Hydrogen production, storage and transportation

The carbon emission intensity of hydrogen-powered UAVs depends primarily on the primary energy source used during the production stage. Hydrogen is categorized by its carbon footprint into gray, blue, and green variants (Zainal et al., 2024). Gray hydrogen exhibits a high emission factor due to the carbon-intensive nature of fossil fuel reforming. Blue hydrogen achieves a lower emission profile through the integration of carbon capture, utilization, and storage (CCUS) technologies. In contrast, green hydrogen enables near-zero carbon emissions by utilizing renewable-powered water electrolysis (de Kleijne et al., 2024). The storage phase contributes to the total carbon burden through the energy required for compression or liquefaction, which is necessary to achieve the energy density required for UAV applications (Aziz, 2018). Furthermore, the transportation of hydrogen via gaseous trailers, liquid tankers, or pipelines introduces additional greenhouse gas releases stemming from fuel consumption during transit. The carbon footprint of the distribution network is further influenced by the energy demands of refueling infrastructure. While liquefaction generates substantial energy-related emissions, pipeline delivery provides an environmentally superior alternative for large-scale logistics (Tayarani and Ramji, 2022).

5.1.3. Stages of operation, maintenance, and recycling

The operation of hydrogen fuel cell UAVs generates zero direct greenhouse gas emissions, representing the primary environmental benefit of this technology. However, the operational phase indirectly influences the total carbon footprint through hydrogen consumption rates, which correlate with upstream production emissions. The implementation of efficient energy management strategies (EMS) determines the overall hydrogen utilization efficiency (Lei et al., 2019). Furthermore, structural weight reduction and aerodynamic optimization decrease energy demand, effectively lowering the cumulative lifecycle emissions (Shen et al., 2024). The maintenance and end-of-life stages also play a pivotal role in environmental mitigation. Since PEMFCs require platinum as a rare-metal catalyst, the recovery and reuse of this precious metal during the recycling phase yields substantial reductions in the carbon burden associated with raw material extraction. This circular approach minimizes the full lifecycle impact and aligns with sustainable manufacturing principles (Song et al., 2025).

5.2. Carbon reduction capacity assessment

The evaluation of carbon reduction potential for hydrogen-powered UAVs focuses on two specific application scenarios: power line inspection and logistics distribution. The task scenarios were conducted in City A in northern China and City B in southern China, as referenced in the literature (Teng et al., 2023). Adopting the Well-to-Wheel (WTW) system boundary allows for the quantification of environmental benefits across the fuel lifecycle. Due to current constraints in manufacturing data, the analysis excludes emissions originating from the production, maintenance, and recycling phases, concentrating instead on operational and fuel-cycle impacts. This exclusion may slightly overestimate the carbon reduction potential, since fuel cell systems and hydrogen storage components involve additional embodied carbon emissions during manufacturing. End-of-life treatment may also affect the total emissions through recycling, recovery, or disposal pathways. Nevertheless, operational energy use and hydrogen production pathways are still expected to dominate lifecycle carbon performance, and the overall comparative conclusions are therefore unlikely to be substantially affected. The carbon emission reduction results presented in this study are based on specific scenario assumptions, and the actual emission reduction performance may vary depending on regional energy structures, hydrogen production pathways, and local infrastructure conditions.

To quantify the environmental impact, CO_2 is used as the primary indicator for greenhouse gas (GHG) emissions. The carbon emissions during the mission scenario are calculated by multiplying the activity data by the corresponding emission factors, as expressed in the following equation:

$$E_i = C_i \times F_i \tag{1}$$

where E_i represents the CO_2 emissions during the mission, C_i denotes the energy consumption, and F_i is the carbon emission factor.

5.2.1. Power line inspection

The mission scenario for power grid inspection involves a 2-h operation at sea level for calm wind conditions. Three UAV types are selected for the carbon emissions comparison, including hydrogen-powered, lithium-battery-powered, and hybrid gasoline-battery-powered models. To minimize energy consumption discrepancies caused by variations in UAV type, this study selects industrial-grade UAVs with a MTOW of 20 kg as the calculation benchmark. Publicly available manufacturer specifications provide the specific parameters for these UAVs, as shown in Table 4.

The carbon emission factors for various energy sources in Cities A and B originate from literature, as shown in Table 5. The disparity in hydrogen-related emissions between these locations stems from the fact that refueling stations in City A operate below capacity. This operational status leads to higher carbon emissions per unit mass of hydrogen during the storage and refueling phases.

The cumulative carbon emissions for the three UAV power systems during a continuous 2-h inspection mission are calculated and compared. As illustrated in Fig. 10, the hydrogen-powered UAV demonstrates a superior carbon reduction profile relative to the lithium-ion and hybrid-electric configurations.

Table 5
Carbon emission factors for different propulsion energy sources (Teng et al., 2023).

Energy source	Region	Carbon emission factor
Hydrogen	City A	5.079 kg (CO_2)/kg (H_2)
	City B	2.249 kg (CO_2)/kg (H_2)
Electricity	City A and City B	0.635 kg (CO_2)/kWh
Gasoline	City A and City B	2.660 kg (CO_2)/L

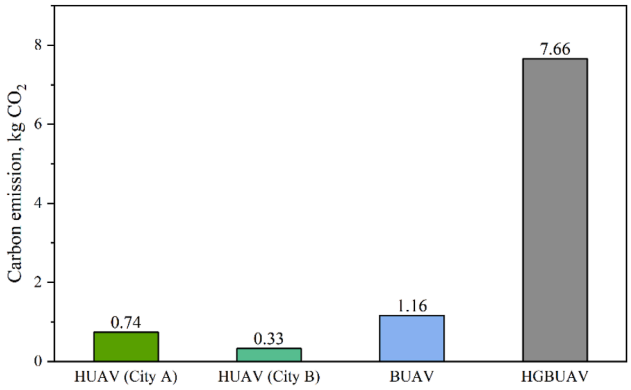


Fig. 10. Carbon emissions for three energy configurations in power line inspection scenarios. HUAV: hydrogen-powered UAV, BUAV: battery UAV, HGBUAV: hybrid gasoline-battery UAV.

For the hydrogen-powered UAV, hydrogen consumption totals 0.15 kg for a 2-h flight. Thus, the carbon emissions for the hydrogen-powered UAV are 0.74 kg in City A and 0.33 kg in City B. Notably, even in City A, where hydrogen infrastructure is in its early stages, the hydrogen-powered UAV's emissions remain lower than the lithium-battery UAV. This demonstrates that the high energy density advantage of hydrogen fuel cells is not only reflected in operational efficiency, but also in their emission reduction potential throughout the entire lifecycle, which surpasses that of traditional battery systems. For the battery-powered UAV, energy consumption totals 1.82 kWh for a 2-h flight, leading to 1.16 kg CO_2 emissions. Although the electric propulsion process itself is pollution-free, the high cruising power consumption of 20 kg-class models results in substantial electricity requirements to sustain flight, which results in higher indirect emissions. Furthermore, in practical operations, lithium-battery UAVs may require multiple round trips due to range limitations, leading to additional redundant energy consumption. For the hybrid gasoline-battery UAV, fuel consumption totals 2.88 L, producing 7.66 kg CO_2 emissions. Compared to the hybrid system, the hydrogen-powered UAV in City B reduced carbon emissions by approximately 95.7%, highlighting the critical role of hydrogen fuel cells in decarbonizing high-load aerial operations.

Table 4
UAV parameters for three propulsion energy sources.

Reference models	Power system	Energy storage specifications	Flight time (min)	Wheelbase (mm)	MTOW (kg)	Average energy consumption
MMC Skylle 1550H (MMC, 2021)	Hydrogen FC	9 L/35 MPa (H_2 tank)	170	1550	19	1.22 g H_2/min
MMC Skylle 1550 (MMC, 2021)	LiHV battery	25000 mAh×12 S (LiHV battery)	75	1550	21	15.2 Wh/min
Honeycomb HC-332H (Honeycomb Aerospace, 2019b)	GX-2 Hybrid power system	5 L (gasoline tank)	210	1560	19.8	0.024 L/min

Note: Energy consumption rates are derived from the ratio of nominal energy capacity to maximum flight endurance. Calculations assume steady-state cruise conditions with a standard mission payload. The density of hydrogen at 35 MPa is taken as 23 g/L in the calculation. The nominal cell voltage for LiHV batteries is 3.8V.

5.2.2. Logistics and distribution

To evaluate the carbon emission reduction potential during cargo transport, this section models a mission scenario involving the delivery of a 15 kg emergency supplies package over a distance of 20 km. The carbon emissions are compared for three delivery modes including hydrogen-powered UAVs, electric light-duty delivery van, and gasoline light-duty delivery van. The specifications of the selected hydrogen-powered UAV in this analysis are shown in Table 6.

Given that the cruising speed for UAVs of this class ranges from 10 to 15 m/s, the cruising speed for mission scenarios is assumed to be 12 m/s. In this 20 km delivery mission scenario, the required flight time for the hydrogen-powered UAV is 27.8 min. The carbon emissions per package for the UAV are 1.30 kg CO_2 in City A and 0.57 kg CO_2 in City B. For the ground transport comparison, the energy consumption and carbon emission factors are listed in Table 7. The calculated carbon emissions for the three delivery modes are compared in Fig. 11. Calculations show that the carbon emissions for the electric light-duty delivery van completing the delivery task are 3.43 kg CO_2 per package, while those for the gasoline light-duty delivery van are 5.21 kg CO_2 per package. Hydrogen-powered UAVs demonstrate lower carbon emission than both ground vehicle alternatives for the assumed single-package delivery conditions. The disparity in carbon emissions between City A and City B stems from differences in the carbon intensity of hydrogen production and the efficiency of refueling infrastructure. However, this conclusion applies exclusively to single-package delivery scenarios. For applications requiring bulk cargo transportation, multiple round-trip flights may increase total carbon emissions for hydrogen-powered UAVs. Therefore, hydrogen-powered UAVs are better suited for scenarios involving small quantities of high-priority or emergency supplies, or for logistics delivery routes inaccessible to ground vehicles.

Table 7
Parameters for ground vehicle energy consumption calculation in logistics distribution scenarios (Stolaroff et al., 2018; Teng et al., 2023).

Vehicle type	Energy consumption	Converted energy consumption	Carbon emission factor
Electric light-duty delivery van	0.96 MJ/km	0.27 kWh/km	0.635 kg CO_2/kWh
Gasoline light-duty delivery van	3.06 MJ/km	0.098 L/km	2.660 kg CO_2/L

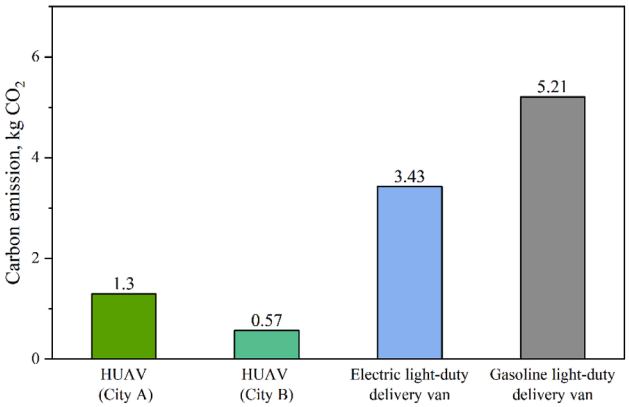


Fig. 11. Comparison of cumulative carbon emissions across three delivery modes.

6. Safety frameworks

Integrating hydrogen energy into UAVs introduces unique hydrogen-related risks alongside conventional challenges (Hadi et al., 2023). Hydrogen is an extremely flammable and explosive gas with a wide flammable range in air (4%-75% by volume) and a low minimum ignition energy (Anekwe et al., 2025). A leak in stored hydrogen contacting an ignition source can readily cause ignition or explosion, generating thermal radiation and overpressure that harm personnel and the environment (Li et al., 2024). A robust framework of regulations, codes, and standards (RCS) is essential for the safe and standardized application of hydrogen-powered UAVs. This section analyzes hydrogen safety issues for hydrogen-powered UAVs by focusing on design requirements, storage and refueling systems, and relevant RCS.

6.1. Design requirements

6.1.1. Leak detection

Establishing an efficient and reliable hydrogen leak detection system is fundamental to ensuring the safe, stable, and efficient operation of hydrogen-powered UAVs. Early and precise identification of hydrogen leaks is essential for preventing fires and explosions to protect ground personnel and onboard equipment (Cristello et al., 2024). Hydrogen leak detection in current hydrogen-powered UAVs primarily relies on electrochemical sensors, which offer high sensitivity, fast response, and low power consumption suitable for onboard integration (Qian et al., 2024). Other sensing technologies, such as metal-oxide semiconductor and optical methods, are under exploration but have not yet been widely adopted in UAV applications. In the design of hydrogen-powered UAVs, hydrogen sensors must be deployed at high-risk locations, including fuel cell systems, hydrogen storage tank valves, and pipeline joints. Strategic sensor placement enables rapid leak detection and timely activation of safety protection mechanisms (Shen et al., 2023). To achieve this precision, Computational Fluid Dynamics (CFD) simulations are increasingly used to model hydrogen dispersion and accumulation within the confined power compartments. These models simulate hydrogen leakage at potential failure points to predict post-leak gas diffusion paths, concentration distributions, and areas where explosive mixtures may form. These results guide the optimization of sensor placement and ventilation design (Guan et al., 2023; Xiao et al., 2026). These CFD-based approaches are directly applicable to the power compartments of hydrogen-powered UAVs to enhance leak detection reliability and overall system safety.

6.1.2. Emergency response

Emergency response strategies for hydrogen-powered UAVs typically include hydrogen leak monitoring, power system shutdown, controlled emergency landing, and safe venting of onboard hydrogen. Sensor systems often implement multi-level concentration thresholds: a lower threshold may trigger operator alerts or ventilation activation, while a higher threshold initiates an automated safety sequence. Upon exceeding the emergency threshold, an electromagnetic valve rapidly isolates the hydrogen supply line, and the fuel cell system enters a protective shutdown mode. The UAV then executes a pre-programmed emergency landing maneuver using residual electrical energy from the propulsion battery or a dedicated backup power source to maintain

Table 6
Parameters of hydrogen-powered UAVs in logistics distribution scenarios (Hydrogen Craft Corporation, 2025).

Reference models	Power (kW)	Payload (kg)	Flight time (min)	Tank	Hydrogen consumption (g H_2/min)
FC30 H2Powered drone	12.6	15	60	2 × 12 L (35 MPa)	9.2

Note: Energy consumption rates are derived from the ratio of nominal energy capacity to maximum flight endurance. Calculations assume steady-state cruise conditions with a standard mission payload. The density of hydrogen at 35 MPa is taken as 23 g/L in the calculation.

flight control during descent. For medium-to-large UAVs operating in densely populated or complex environments, a parachute recovery system may be incorporated to mitigate ground impact risks (Kumar et al., 2023). Additionally, the hydrogen storage system is equipped with a Temperature-Pressure Relief Device (TPRD). In fire scenarios, the TPRD activates to safely vent hydrogen and prevent tank over-pressurization to reduce the risk of catastrophic failure (Sun and Li, 2021).

6.1.3. Safety design

Hydrogen has an extremely low minimum ignition energy in air of approximately 0.02 mJ, which makes it susceptible to ignition from small sparks or electrostatic discharges (Xu and Xie, 2015). To address these ignition risks, safety design for hydrogen-powered UAVs focuses on two objectives: preventing ignition sources and mitigating the consequences of hydrogen release. Prevention of ignition sources includes electrostatic and electrical safety measures. In areas where hydrogen leakage may occur, the UAV structure and components must be designed to avoid electrostatic accumulation, typically using conductive materials and grounding techniques (Mitolo et al., 2025). The electrical system requires continuous monitoring of insulation resistance to detect degradation, along with multiple short-circuit protection mechanisms such as fast-acting fuses, overcurrent protectors, and electrical isolation devices to prevent sparking or overheating (Ma et al., 2022; Short, 2012). Mitigation of hydrogen accumulation relies on effective ventilation. Given the low density of hydrogen, leaked gas rises and accumulates in upper regions or corners of enclosed compartments housing power systems. Properly positioned ventilation ports facilitate hydrogen dispersion and reduce the risk of flammable mixture formation (Song et al., 2024).

6.2. Hydrogen storage and refueling

6.2.1. Hydrogen storage

The integration of high-pressure hydrogen storage into UAVs introduces safety challenges distinct from ground-based systems, primarily due to weight constraints, dynamic flight loads, and limited crash protection. Most hydrogen-powered UAVs use Type III or Type IV composite pressure vessels operating at 35–70 MPa with volumes below 20 L. While these tanks offer high gravimetric density, their composite construction of these vessels presents specific vulnerabilities in aerial applications. During flight, the storage system is subjected to vibration, thermal cycling, and maneuver-induced accelerations, which may accelerate material fatigue or compromise seal integrity at valve interfaces (Shen et al., 2024). In the event of a crash, the combination of high internal pressure and impact forces increases the risk of tank rupture or hydrogen release. To mitigate this risk, UAV-mounted tanks are typically housed within reinforced compartments and isolated from ignition sources, though the limited structural mass available for crash absorption remains a design constraint.

Thermal management is another critical concern. Unlike ground vehicles, UAVs lack active cooling capacity for the storage system. Prolonged operation in high-ambient-temperature environments or under direct solar exposure can elevate tank temperature, leading to a pressure increase. Continuous monitoring of temperature and pressure is therefore essential to avoid exceeding design limits. LH_2 storage, while offering higher volumetric energy density, is not currently viable for most small or medium UAVs due to boil-off losses, the mass of vacuum insulation, and the absence of reliable lightweight cryogenic valves. Its use remains confined to conceptual studies for high-altitude long-endurance platforms (Adler and Martins, 2023).

6.2.2. Hydrogen refueling

Unlike refueling of ground vehicles, hydrogen replenishment for UAVs typically occurs in uncontrolled or temporary environments, often without dedicated infrastructure. Most operational UAVs are refueled by using portable high-pressure cylinders or compact mobile units rather than fixed hydrogen refueling stations (Kim et al., 2022). These field-based setups frequently lack reliable grounding, forced ventilation, and operator shielding, which elevates the risk of ignition during connection, transfer, and disconnection.

Primary safety challenges involve maintaining reliable seals for quick-disconnect couplings over repeated cycles, managing electrostatic buildup on non-conductive landing gear, and ensuring a complete purge of residual hydrogen from fuel lines. To address these issues, refueling interfaces are typically designed with automatic shut-off valves and integrated leak checks. Hydrogen sensors are commonly deployed near the refueling port to detect anomalies during gas transfer. If a leak is detected, the system can interrupt flow and trigger local alarms (Li et al., 2023). Operator training remains important, but given the trend toward simplified field operations, safety increasingly relies on fail-safe hardware design and automated monitoring rather than procedural compliance alone.

6.3. Regulations, codes, and standards

The deployment of hydrogen-powered UAVs introduces safety considerations that are not fully addressed by existing aviation or ground-based hydrogen regulations. Current regulatory frameworks for these systems are largely derived from standards developed for automotive, stationary storage, or manned aviation applications. While relevant provisions from ISO, SAE, CGA, and national codes provide a foundational reference, specific requirements for small unmanned aircraft, particularly regarding onboard storage, refueling in field conditions, and emergency response, remain limited or under development.

In practice, RCSs inform the design of hydrogen-powered UAVs by specifying minimum safety and performance criteria for key components such as hydrogen storage tanks, fuel cells, supply systems, and refueling interfaces. These criteria support airworthiness assessments by offering a basis for integrating hydrogen propulsion into existing UAV certification schemes (U.S. Department of Energy (DOE), n.d.).

Dedicated guidance remains scarce. Most implementations rely on adaptations of standards originally intended for other sectors. A summary of relevant documents is provided in Table 8. Japan's Ministry of Economy, Trade and Industry (METI) published the *Safety Usage Guidelines for High-Pressure Gases in Hydrogen Fuel Cell-Powered Drones* in 2020, which define responsibilities for manufacturers and operators concerning tank handling, operational procedures, and safety precautions. In China, GB/T 38954-2020 provides technical requirements for hydrogen fuel cell power systems used in UAVs, covering aspects such as general requirements, technical requirements, and test methods. At the international level, ISO/TR 15916, *Basic Considerations for the Safety of Hydrogen Systems*, provides general safety principles applicable to UAV hydrogen system risk management. From a practical development perspective, GB/T 38954-2020 and the METI guidelines remain among the few documents directly addressing hydrogen fuel cell UAV applications, while international standards such as IEC 62282 series, ISO/TR 15916, ISO 14687, and SAE J2579:2023 provide broader technical and safety principles applicable to hydrogen-powered UAV development.

Nevertheless, significant gaps persist. The Canadian Hydrogen Codes and Standards Roadmap identifies hydrogen-powered UAVs as a full gap (Natural Resources Canada, 2024). Three key deficiencies are evident. First, no certification standards exist specifically for hydrogen storage containers in UAVs. Existing standards for automotive or industrial vessels use test protocols for impact, vibration, and rapid decompression that do not reflect UAV flight or crash dynamics. Second, operational requirements including mobile refueling, vibration resistance, high-altitude performance, and low-temperature operation lack dedicated infrastructure guidelines or standardized procedures. Third, airworthiness certification pathways for hydrogen-powered UAVs remain immature. Although the FAA has outlined a roadmap for

Table 8
Selected regulations, codes, and standards relevant to hydrogen-powered UAVs.

Standard/Guideline	Issuing body	Original scope	Applicability to hydrogen-powered UAVs	Key limitations
SAE J2579:2023	SAE International	Hydrogen fuel systems for road vehicles	Reference for hydrogen storage safety and leak tolerance	Ground-vehicle assumptions; not suitable for airborne systems
ISO/TR 15916:2026	ISO	General hydrogen safety principles	Supports hazard identification and qualitative risk assessment	Non-binding; lacks UAV-specific operational context
CGA G-5	Compressed Gas Association (USA)	Safe handling of compressed hydrogen	Applicable to hydrogen storage and ground handling for UAVs	Focused on industrial and stationary applications
NFPA 2	NFPA (USA)	Hydrogen technologies safety	Relevant to hydrogen storage and refueling during UAV ground operations	Does not address airborne hydrogen systems
NFPA 55	NFPA (USA)	Compressed gases and cryogenic fluids	Guidance for hydrogen storage facilities supporting UAV operations	Facility-based requirements dominate
IEC 62282 series	IEC	Fuel cell technologies	Relevant to fuel cell stack safety and performance evaluation	UAV integration and flight conditions not considered
IEC 60079 series	IEC	Explosive atmospheres	Reference for explosion protection of electrical equipment	Not tailored to compact UAV systems
ISO 14687	ISO	Hydrogen fuel quality	Ensures fuel cell durability and performance	No consideration of UAV operational variability
ISO 19880-1	ISO	Hydrogen refueling stations	Relevant to UAV ground refueling system design	Infrastructure-oriented; not portable-system focused
GB/T 38954-2020	SAC (China)	Hydrogen fuel cell power systems for UAVs	Directly applicable technical standard for UAV fuel cell systems	Limited international recognition
METI Hydrogen UAV Guidelines	METI (Japan)	Hydrogen fuel cell UAV operations	One of the few UAV-oriented hydrogen safety guidelines	National scope; lacks quantitative certification criteria
FAA Hydrogen-Fueled Aircraft Safety and Certification Roadmap	FAA (USA)	Hydrogen-powered aircraft certification	Provides regulatory insight into hydrogen aviation safety	Primarily based on Part 23/25/27/29 manned aircraft framework
ISO/CD 25013 (Draft)	ISO	Hydrogen cylinders for fuel-cell UAVs	First draft international standard targeting UAV hydrogen cylinders	Still under development; not yet enforceable

hydrogen aircraft safety, it does not include provisions tailored to unmanned platforms.

From a safety perspective, the development of RCS for hydrogen-powered UAVs would benefit from a three-tier framework that address risks across the lifecycle, from components to integrated systems and field operations. (1) Component and subsystem standards layer. UAV-specific certification and test protocols are needed for hydrogen system components, including storage tanks, fuel cell stacks, and pressure relief valves. These protocols should account for operational conditions unique to UAVs, such as sustained vibration, drop and crash impacts, and high-rate discharge events. (2) System integration and airworthiness standards layer. Future standards should incorporate research findings on hydrogen dispersion around UAV airframes, hydrogen embrittlement associated with flight-induced cyclic loading, flame propagation in confined compartments, and localized thermal runaway in fuel cell systems. Ground and flight testing could support the validation of emergency response strategies. A dedicated subset of airworthiness standards would be required to address container protection, venting pathway design, thermal management, and electrical isolation. (3) Operational and infrastructure standards layer. Guidance for the safe use of portable refueling units and mobile hydrogen storage in field environments remains limited. Such guidance should include requirements for leak detection, ambient monitoring, and operator competency. Standardized procedures for post-crash scenarios, such as hydrogen release mitigation and fire response, would support consistent incident management.

7. Conclusions and prospects

Hydrogen-powered UAVs have the advantages of extended endurance, broad temperature tolerance, and zero direct emissions, which mitigate the inherent limitations of battery-electric and internal combustion platforms. Current implementations prioritize hybrid propulsion systems, integrating PEMFCs with auxiliary energy sources to compensate for slow dynamic responses and low power density. Advancing onboard hydrogen storage requires further improvements in the gravimetric and volumetric efficiency of composite high-pressure tanks.

Hydrogen-powered UAVs exhibit substantial carbon reduction potential within a lifecycle-oriented framework. While upstream hydrogen pathways dominate overall emissions, the high energy density of hydrogen enables clear advantages in endurance-intensive inspection and single-package logistics scenarios. Additional carbon footprint contributions stem from the manufacturing of the airframe, hydrogen storage tanks, and platinum catalysts within fuel cell stacks.

Safety management must address three interconnected dimensions: design integration, storage/refueling, and regulatory frameworks. Effective risk mitigation necessitates robust leak detection, emergency venting, and multi-layered protection systems. However, dedicated regulations, codes, and standards (RCS) remain nascent. Existing guidelines, largely adapted from automotive or manned aviation domains, fail to account for UAV-specific dynamics such as field refueling, vibration exposure, and crash impact. The absence of a standardized framework tailored to small unmanned platforms constitutes the most significant barrier to systematic safety validation and regulatory acceptance.

In the near term (2026–2030), hydrogen-powered UAVs are already demonstrating clear advantages in long-endurance missions such as industrial inspection and defense, with ongoing early commercial scaling. However, limitations in storage, infrastructure, and cost mean that hydrogen-powered UAVs will complement rather than replace battery systems. In the medium term (2030–2040), advances in fuel cell durability and hydrogen supply chains are expected to enable widespread mid-range commercial logistics. Crucially, these UAVs serve as essential flying testbeds for hydrogen aviation, maturing the technologies required for the transition into hydrogen-powered regional aircraft. While hydrogen is poised to anchor the future of sustainable, zero-emission regional transport, hydrogen-powered UAVs will remain a key enabling technology across this transition horizon.

CRediT authorship contribution statement

Xuefang Li: Conceptualization, Formal analysis, Funding acquisition, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Qianru Hong:** Formal analysis, Writing – original draft. **Richard Chahine:** Conceptualization, Supervision, Writing – review & editing. **Mingjia Chen:** Funding acquisition, Project administration. **Fei Wang:** Data curation, Investigation. **Qingxin Ba:** Funding acquisition, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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