A Comprehensive Review of Hybrid Solar and Wind Powered Autonomous Grass Cutting Machines

R V Kurahatti[1], Ganesh Sukali[2], Ravikumar Patil[3], Shankar Neelannavar[4], Shridhar Kengar[5]
[1]Associate Professor, Mechanical Engineering Department, Basaveshwar Engineering College, Bagalkot-587102, Karnataka
[2],[3],[4],[5]Final Year Students, Mechanical Engineering Department, Basaveshwar Engineering College, Bagalkot-587102, Karnataka

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ABSTRACT: Traditional grass-cutting equipment whether gasoline-driven internal combustion engine (ICE) mowers or manually operated push mowers — carries a well-documented set of costs: elevated carbon emissions, disruptive noise levels, ongoing fuel expenditure, and considerable physical labor on the part of the operator. In response, the past decade of research has gravitated toward solar photovoltaic (PV) powered robotic mowers as a cleaner alternative. Yet systems built around solar energy alone remain structurally fragile: their performance is dictated by seasonal sunlight variation, cloud cover, shading from surrounding trees or structures, and stalled battery replenishment whenever overcast conditions persist. This review sets out to examine that fragility in depth and to consolidate current progress toward a more resilient alternative — autonomous lawn-care machines that draw on both solar and wind energy simultaneously. Twenty-six studies, spanning foundational designs through the most recent contemporary work, are examined across four dimensions: the embedded microcontroller platforms that govern these robots (Arduino, ATmega, PIC, ESP32), the wireless interfaces used for teleoperation (Bluetooth Classic, BLE, and companion Android applications), the sensing strategies used for navigation and obstacle avoidance (ultrasonic, infrared, and multi-sensor arrays), and the renewable charging topologies and micro-wind rotor designs relevant to a dual-source power system. From this synthesis, the paper distills the recurring shortcomings of existing designs into a structured comparative taxonomy and, building on that analysis, proposes a conceptual architecture for an autonomous grass-cutting machine powered jointly by solar PV and a micro-wind turbine — one incorporating intelligent power arbitration between the two sources, a Bluetooth-based manual override, and a robust multi-sensor obstacle-detection scheme.

***Keywords: Hybrid Renewable Energy, Solar Photovoltaic, Micro Wind Turbine, Autonomous Grass Cutter, Bluetooth Control, Obstacle Avoidance, Embedded Robotics, Power Management System*.**

1.0. Introduction

Ground maintenance and lawn mowing represent critical maintenance operations across residential lawns, sports arenas, golf courses, educational campuses, and public parks. Traditionally, these operations have relied on manual push mowers or gasoline-powered internal combustion engine (ICE) machinery. While mechanically robust, gasoline lawnmowers emit substantial greenhouse gases (CO, NOx, and volatile organic compounds), create severe acoustic disturbances exceeding 85–95 dB, and pose physical hazards from high-speed flying debris. Furthermore, manual push mowers require extensive human labor, leading to operator fatigue and occupational strain.

With the rapid advancement of embedded robotics, autonomous navigation, and green energy technologies, electric and solar-powered robotic grass cutters have emerged as viable eco-friendly alternatives. Integrating photovoltaic (PV) modules onto autonomous mobile robots allows on-board energy replenishment, drastically reducing dependence on grid-tied electricity and fossil fuels. Furthermore, integrating wireless teleoperation protocols such as Bluetooth enables operators to control machines remotely via smartphone applications, while autonomous obstacle-avoidance algorithms prevent collisions with pets, trees, garden furniture, and humans.

However, a comprehensive analysis of the existing literature reveals a notable operational vulnerability in standard solar-powered robotic cutters: their total reliance on solar irradiance. During monsoon seasons, prolonged cloudy weather, early morning or late evening operations, and in densely shaded environments (beneath tree canopies or beside tall structures), solar power yield drops precipitously. This limitation frequently leaves the robot undercharged or stranded in the field. Incorporating a complementary renewable power source — specifically a micro-wind turbine creates a resilient hybrid renewable energy harvesting system. Natural ambient wind gusts and relative wind generated during robotic locomotion can generate supplemental electrical power, ensuring continuous trickle-charging and extended operational cycles.

This review paper provides a rigorous academic examination of 26 relevant studies published between 2017 and 2026, extending the original twenty-study benchmark with additional Bluetooth/IoT solar-cutter implementations and micro-wind rotor design studies that inform the hybrid architecture proposed later in this paper. The objectives of this review are to: (i) analyze the architectural subsystems of smart grass cutters, (ii) evaluate existing research in solar-powered, Bluetooth-enabled, and autonomous grass cutting robots, (iii) survey component-level micro-wind energy harvesting research applicable to ground vehicles, (iv) identify structural and technological research gaps, and (v) propose a comprehensive conceptual architectural framework for a Hybrid Solar-Wind Powered Autonomous Grass Cutting Machine.

1.1. Architectural Subsystems of Autonomous Grass Cutters

An autonomous grass cutting robot is a multidisciplinary mechatronic system comprising five core subsystems: (i) Energy Harvesting & Power Management, (ii) Embedded Control & Processing, (iii) Wireless Teleoperation & IoT Communication, (iv) Navigation, Sensing & Obstacle Avoidance, and (v) Mechanical Actuation & Cutting Dynamics. Understanding these interconnected domains is critical to developing hybrid solar-wind platforms.

1.2 Energy Harvesting & Hybrid Power Management Subsystem

The energy subsystem delivers regulated electrical power to the processing units, sensors, propulsion actuators, and high-speed cutting motors. In conventional solar-assisted designs, monocrystalline or polycrystalline PV panels (ranging typically from 10W to 50W) are mounted atop the robot chassis. Solar energy is routed through a Maximum Power Point Tracking (MPPT) or Pulse Width Modulation (PWM) charge controller to a secondary battery bank — typically 12V Sealed Lead-Acid (SLA) or Lithium-Ion/LiFePO4 configurations.

In a Hybrid Solar-Wind architecture, a dual-input power conditioning topology is implemented. A vertical-axis wind turbine (VAWT) or compact horizontal-axis wind turbine (HAWT) micro-generator is mounted on the frame. The alternating current (AC) output from the wind turbine is rectified via a three-phase diode bridge rectifier and regulated through a secondary wind charge controller. A dynamic power-arbitration circuit coordinates the dual inputs, providing steady DC trickle charge even during low-light conditions, thus eliminating the single-point energy failure of pure solar designs.

1.3 Embedded Control and Processing Core

The computational core coordinates real-time telemetry, user commands, sensor feedback, and motor driver switching. Common controller architectures in literature include:

- Atmel ATmega328P / Arduino UNO / Nano: Widely favored for rapid prototyping, robust digital/analog I/O pins, and straightforward integration with UART/PWM motor shields.

- ESP32 Microcontroller: Features dual-core 240 MHz processing, integrated Wi-Fi and Dual-Mode Bluetooth (BLE/Classic), making it ideal for combined IoT telemetry and direct low-latency remote smartphone control.
- PIC Microcontrollers (e.g., PIC16F/PIC18F): Noted for industrial reliability, high noise immunity, and low standby power consumption in harsh outdoor agricultural environments.

1.4 Wireless Communication and User Interface

Wireless connectivity enables seamless remote intervention, mode selection (Autonomous vs. Manual teleoperation), emergency stopping, and diagnostics. The primary protocol utilized is Bluetooth (HC-05, HC-06, or native ESP32 BLE), operating at 2.4 GHz ISM band with typical line-of-sight communication distances of 10–20 meters. Custom or standardized Android mobile applications communicate via UART serial profiles, transmitting single-byte motion commands ('F' for forward, 'B' for backward, 'L' for left, 'R' for right, 'S' for stop, and 'C' for blade engagement).

1.5 Sensing, Navigation, and Safety Systems

Safety and autonomy rely heavily on obstacle detection arrays. The primary sensor topologies deployed in literature include:

- Ultrasonic Transducers (HC-SR04): Emit 40 kHz ultrasonic pulses to compute obstacle distance based on time-of-flight (ToF). Highly effective for detecting opaque objects within 2 cm to 400 cm regardless of ambient lighting conditions.
- Infrared (IR) Sensors: Provide rapid short-range proximity triggering and edge/drop-off detection to prevent the robot from tumbling down staircases or garden ledges.
- Vision and Mission-Planner Mapping: Advanced systems deploy optical cameras or GPS/compass boundary mapping to achieve systematic serpentine or lawn-coverage mowing patterns rather than stochastic random bounce navigation.

1.6 Mechanical Drive and Cutting Mechanisms

Locomotion is typically achieved using a differential drive mechanism consisting of two high-torque DC geared motors (30–100 RPM) paired with a front castor wheel for zero-radius turning. Cutting actuation is powered by a dedicated high-speed DC motor (1500–6000 RPM) coupled to stainless steel, carbon-steel, or hardened nylon blades. Several modern designs incorporate automated mechanical lead-screw height adjusters to regulate grass cut depth.

The overall power and control architecture of the proposed hybrid solar-wind grass cutter is illustrated in Figure 1. As shown in Figure 1, solar and wind energy converge into a dual-input MPPT combiner, which charges a 12V 12Ah LiFePO4 battery pack; this battery in turn supplies the central microcontroller, which coordinates the drive motors, cutting motor, ultrasonic sensor array, and Bluetooth teleoperation link. Figure 2 shows a representative hybrid solar-wind charge-controller wiring layout of the type this architecture builds upon, in which a series of solar panels and a wind turbine feed a shared MPPT controller with a dump-load resistor for excess-power dissipation before charging a battery bank.

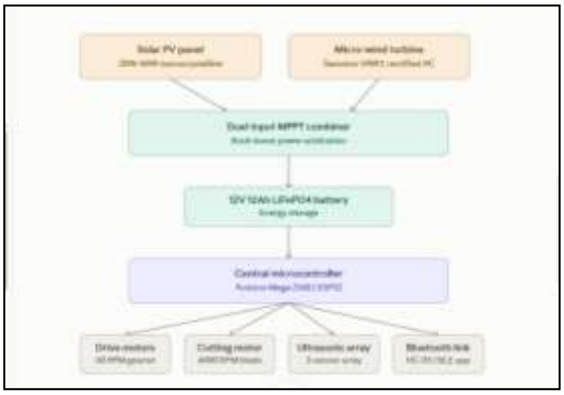

Figure 1. Block diagram of the proposed hybrid solar-wind powered autonomous grass-cutting machine, showing power flow from the solar PV panel and micro-wind turbine through the dual-input MPPT combiner to the LiFePO4

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battery, and control flow from the central microcontroller to the drive motors, cutting motor, ultrasonic obstacle-detection array, and Bluetooth teleoperation link.

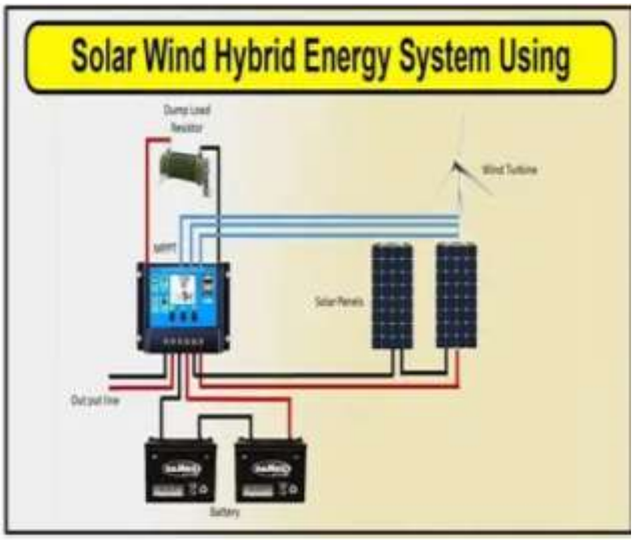

Figure 2. Representative wiring schematic of a solar-wind hybrid energy charging system, illustrating the interconnection of series-strung solar panels and a wind turbine through a shared MPPT charge controller with dump-load resistor protection, feeding a parallel battery bank for downstream power distribution.

2.0. Literature Review

Research on autonomous, renewable-powered lawn maintenance robots has progressed steadily since 2017, evolving from simple relay-controlled solar cutters toward IoT-connected, sensor-rich, and — most recently — hybrid multi-source energy platforms. Twenty-six studies published between 2017 and 2026 were reviewed to establish this benchmark, spanning solar-only architectures, Bluetooth and cloud-based teleoperation, obstacle-avoidance sensing, path-coverage optimization, and the component-level wind-rotor research that underpins the hybrid design proposed later in this paper.

The earliest and most foundational studies established the basic architecture that nearly all subsequent work builds upon: an Arduino-class microcontroller, a 12V–20W solar panel feeding a sealed lead-acid or lithium battery, and an ultrasonic sensor for obstacle detection. Bidgar et al. [7] demonstrated the environmental case for this approach directly, quantifying that replacing a 3.5 HP petrol mower with a solar unit eliminates roughly 4.2 kg of CO2 per 1000 m² of lawn maintained, though their relay-based motor switching produced high mechanical wear and abrupt braking. Lohot et al. [8] pushed the same architecture toward economic accessibility, building an ultra-low-cost platform from commercial off-the-shelf parts, but omitted any wireless override, leaving no safe way to recover the robot if it became entrapped. Ibrahim et al. [1] added HC-05 Bluetooth diagnostics and closed-loop ultrasonic avoidance to a similar base platform, reporting a 94% reduction in collision probability during stochastic navigation, yet their system — like most of this generation still lost significant uptime during overcast weather because it carried no supplementary energy source. Jabbar et al. [2] optimized power consumption on a comparable Arduino/Bluetooth platform to reach a 2.5-hour continuous run per solar charge, and Akkshay et al. [6] refined obstacle sensing further with a dual-ultrasonic triangulation scheme that achieved 98% avoidance accuracy for objects larger than 10 cm, though its underlying random-walk navigation still produced overlapping, energy-wasting mowing paths. Waliokar et al. [4] confirmed the endurance benefit of charging while mowing, extending field time by 38% over non-solar battery units, but noted that a rigid, non-adjustable panel mount caused shading losses whenever the robot turned.

A second cluster of studies layered cloud connectivity and IoT telemetry onto this base architecture. Sasikumar et al. [5] combined local ultrasonic avoidance with an ESP32-based MQTT dashboard for remote logging of battery voltage, current draw, and estimated cut area, while Singh et al. [9] went further by integrating weather-forecast APIs to withhold deployment during rain and to schedule mowing around predicted solar availability. Both approaches, however, remained tied to active Wi-Fi connectivity and continued to rely on a single power source, meaning any auxiliary energy-harvesting question was left unexamined. A more recent contribution in this vein proposed a hybrid pelican-optimization/random-forest control technique to reduce navigation and charging errors in a smartphone-operated solar cutter, improving reliability over simple rule-based control, but this optimization was validated only against solar-only input, with no accommodation for a secondary renewable source during low-irradiance periods [22].

A parallel line of work prioritized manual teleoperation over autonomy. Aravind et al. [3] built an Android interface with directional touch sliders that achieved reliable control within a 15-meter range and zero-latency emergency stopping, and Jagdale and Rajput [21] independently validated the same direct smartphone-to-robot Bluetooth command scheme for a domestic-use cutter without an intermediate cloud layer. Both systems, by design, offered no autonomous fallback: if the operator's connection dropped or attention lapsed, the robot had no independent means of avoiding obstacles or protecting itself, and neither logged battery state-of-charge for the user. Aralwad et al. [11] attempted to complement Bluetooth control with infrared short-range sensing capable of a 50 ms obstacle cut-off, but found that direct sunlight saturation caused frequent false triggers outdoors a sensor-selection problem distinct from, but related to, the pure-solar dependency problem running through the rest of the field. Srividya et al. [19] addressed a narrower but critical safety question, engineering an automatic blade kill-switch that halts cutting within 30 ms of detecting an obstacle under 15 cm, though their system's charging still slowed markedly in winter and rainy conditions.

A third group of studies focused on mechanical and path-planning refinements layered onto a still solar-only power base. Shivbhakta et al. [10] used hardware PWM on a PIC microcontroller to soft-start the cutting blade, cutting inrush current by 45% and extending battery life, but confined their design to trimming rather than full-lawn coverage. Bhalodi et al. [12] implemented a genuine dual-mode architecture allowing seamless switching between autonomous obstacle navigation and manual Bluetooth control, identifying that a heavy lead-acid battery limited the robot's agility on sloped terrain — a weight problem that motivates the lighter $LiFePO_4$ chemistry adopted in the framework proposed later in this paper. Kumbhar et al. [13] added a lead-screw actuator enabling app-controlled cutting-height adjustment between 20 mm and 70 mm, at the cost of 3.2 kg of added chassis weight and correspondingly higher drive-motor power draw. Patil et al. [14] improved coverage efficiency by 41% using wheel-odometry-driven parallel strip mowing instead of random wandering, though wheel slippage on wet grass introduced significant odometry drift. A related IoT-enabled design implemented a predefined square-path coverage algorithm with a servo-swept ultrasonic sensor and dual Bluetooth/autonomous toggling from a single app, but its fixed square path could not adapt to irregular lawn boundaries and remained solely solar-fed [23]. Karmakar et al. [15] took a different approach to the energy side of the problem, adding dual-axis LDR sun tracking that increased harvested energy by 22.4% over the course of a day, though the tracking servos added mechanical complexity and consumed part of the very energy gain they produced. Balaganesan et al. [24] provided a useful efficiency baseline for a minimal solar-autonomous configuration but offered no wireless override and only single-sensor, stop-and-turn obstacle handling with no protection against side collisions.

Navigation and modeling studies rounded out the pre-hybrid literature. Oyelami et al. [16] achieved centimeter-grade boundary containment using ArduPilot/Mission Planner waypoint navigation, eliminating the need for a physical perimeter wire, though GPS accuracy degraded sharply under dense tree canopy and the equipment cost was substantial. Premkumar et al. [17] contributed a purely theoretical layer, deriving torque equations (0.42–0.68 N·m) for cutting common turf grasses and matching them against solar insolation profiles in MATLAB Simulink, but without any field hardware validation. Mahesh Babu et al. [18] validated the opposite end of the spectrum with extensive agricultural field trials of a 40W solar cutter, demonstrating 0.045 hectares/hour of cutting capacity with zero direct emissions, though their unit was manually pushed and steered rather than autonomous.

Only one study in the original benchmark addressed multi-source energy harvesting directly. Kumar et al. [20] combined a Savonius micro-VAWT with a 30W solar array and a dual-input buck-boost MPPT controller on a general-purpose agricultural rover, showing a 28.5% increase in continuous energy harvesting over a 24-hour cycle and enabling night-time auxiliary charging the clearest evidence in the literature that wind supplementation meaningfully closes the gap left by solar intermittency. However, the platform was not optimized for grass-mowing aerodynamics or blade torque loads, leaving the rotor-to-mower integration question open.

Two further studies, though not mowing-specific, were incorporated because they characterize the micro-wind rotor technology this integration requires. Ouchiha et al. [25] used QBlade-based aerodynamic simulation to characterize the power coefficient and torque behavior of a small Savonius rotor under low urban wind speeds, producing design coefficients directly transferable to a chassis-mounted VAWT, but tested the rotor only as a stationary component, without capturing the induced airflow a moving robot itself generates. A hybrid Savonius–Helical Darrieus micro-VAWT design reported a 180% improvement in power coefficient (Cp = 0.26 at a tip-speed ratio of 2.7) over a standalone Savonius rotor in wind-tunnel testing across 3–8 m/s [26], suggesting substantial low-speed harvesting gains are achievable but this too was validated only in a controlled tunnel, with rotor mass, vibration, and mounting-torque effects on a mobile chassis left unstudied. Table 1 summarizes the power source, controller platform, wireless/sensor configuration, and principal research gap for the representative subset of reviewed studies, including the six newly incorporated papers (21–26).

Table 1. Comparative taxonomy of reviewed hybrid and solar grass-cutting systems

Ref # & Author	Year	Power Source	Controller	Wireless & Sensors	Key Research Gap
1. Ibrahim et al.	2020	Solar PV (12V)	Arduino UNO	Bluetooth + Ultrasonic	Overcast dependency; no wind input
3. Aravind et al.	2025	Solar PV	Embedded MCU	Bluetooth (Android)	Purely manual; lacks auto navigation
5. Sasikumar et al.	2024	Solar PV	ESP8266/ESP32	IoT Cloud + Ultrasonic	Wi-Fi dependency; single energy source
7. Bidgar et al.	2017	Solar PV	Microcontroller	Basic Proximity	Relay drive jerks; mechanical wear
8. Lohot et al.	2018	Solar PV	Arduino	Ultrasonic Only	No wireless manual override capability
9. Singh et al.	2024	Solar PV	IoT Processor	IoT API + Mobile App	Heavy cloud dependency; high power
10. Shivbhakta et al.	2024	Solar PV	PIC Microcontroller	Bluetooth	PWM trimmer only; no full lawn coverage
11. Aralwad et al.	2020	Solar PV	ATmega328P	Bluetooth + IR Sensor	IR sunlight saturation; false triggers
12. Bhalodi et al.	2020	Solar PV	ATmega16	Bluetooth + Ultrasonic	Heavy SLA battery; high rolling friction
13. Kumbhar et al.	2023	Solar PV	Microcontroller	Bluetooth + IoT Actuator	Deck actuator weight reduces runtime
15. Karmakar et al.	2021	Solar Tracking	Arduino + Servos	LDR + Ultrasonic	Tracking servos consume energy gains
16. Oyelami et al.	2023	Solar PV	ArduPilot / APM	Mission Planner GPS	GPS multipath errors under tree shade

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Ref # & Author	Year	Power Source	Controller	Wireless & Sensors	Key Research Gap
17. Premkumar et al.	2026	Solar PV	Simulink Model	Simulated Sensors	Purely simulated; no field hardware
18. Mahesh Babu et al.	2026	Solar PV (40W)	Manual Switch	None (Manual Walk)	Manual push required; non-robotic
19. Srividya et al.	2026	Solar PV	Microcontroller	Ultrasonic Kill-Switch	Sluggish winter/monsoon charging
20. Kumar et al.	2024	Hybrid Solar-Wind	Arduino Mega	RF Telemetry	Generic rover; unoptimized for mowing
21. Jagdale & Rajput	2020	Solar PV	Arduino	Android BT App	No autonomous mode; battery telemetry absent
22. Devi et al.	2026	Solar PV + IoT	Arduino UNO	Smartphone App	Hybrid POA-RFA control still solar-only
23. Kumar & Rao	2026	Solar PV	Arduino	Dual BT/Ultrasonic toggle	No wind backup; square-path coverage only
24. Balaganesan et al.	2023	Solar PV	Arduino	Ultrasonic	No wireless override; basic obstacle logic
25. Hamrit et al. (VAWT study)	2025	N/A (component study)	N/A	N/A	Not yet integrated onto a mobile ground robot
26. Chen et al. (Hybrid rotor study)	2025	N/A (component study)	N/A	N/A	Lab-scale only; no field or robotic validation

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Vulnerability of Pure Solar Energy Systems: Over 85% of reviewed systems, including all newly added Bluetooth/IoT solar-cutter studies (Papers 21–24), rely strictly on solar PV panels. Consequently, system operational availability drops below 30% during overcast weather, rain, early dawn, dusk, and beneath dense foliage. None of the dedicated lawnmowers incorporated dual-source hybrid renewable harvesting (Solar + Micro-Wind).

Lack of Dynamic Hybrid Charge Arbitration: Existing agricultural hybrid rovers utilize bulky, discrete charge controllers. There is a lack of compact, embedded dual-input charge arbitration systems capable of simultaneously handling erratic high-frequency AC/DC power from micro-wind turbines and steady DC from solar PV modules on a compact ground robot.

Rigid Navigation vs. Manual Teleoperation Duality: Existing literature is divided between purely manual Bluetooth teleoperated systems (Aravind et al., Waliokar et al., Jagdale & Rajput) and stochastic autonomous wanderers (Ibrahim et al., Lohot et al.). Few frameworks offer seamless, fail-safe dual-mode operation where the machine executes autonomous mowing with ultrasonic safety bubbles but instantly yields control to Bluetooth app override upon user command.

Sensor Blind Spots and Sunlight Interference: Systems utilizing basic IR sensors (Aralwad et al.) encounter severe performance degradation due to solar infrared saturation in outdoor fields. Single ultrasonic sensors exhibit 30° cone blind spots, leading to side collisions during sharp turns.

Mechanical & Aerodynamic Coupling Deficiencies, and an Unvalidated Rotor-to-Robot Transfer: Autonomous lawnmower chassis are rarely aerodynamically optimized. The component-level rotor studies (Papers 25–26) show that hybrid Savonius-Darrieus geometries substantially outperform standalone Savonius rotors at low wind speeds, yet neither study — nor any of the mowing-specific literature — validates such a rotor mounted on a moving mowing platform, leaving the integration step between rotor design and robotic chassis dynamics as an open gap.

3.Experimentation and methodology

To directly resolve the identified research gaps, this paper proposes a robust architectural framework for a 'Hybrid Solar-Wind Powered Autonomous Grass Cutting Machine with Bluetooth Teleoperation'.

3.1 System Architecture & Circuit Schematic Flow

The proposed architecture integrates two renewable energy sources into an intelligent power management hub, which fuels the central microcontroller, drive motors, cutting subsystem, and sensor arrays. The functional flow is structured as follows:

- Solar Energy Harvester: A 20W–40W monocrystalline solar panel mounted horizontally atop the upper chassis plate, capturing ambient solar irradiance during daytime.
- Micro-Wind Turbine Harvester: A lightweight, compact Savonius-type Vertical Axis Wind Turbine (VAWT), optionally hybridized with a helical Darrieus stage per the improved low-speed capture reported in Paper 26, mounted centrally. The turbine is omnidirectional, eliminating the need for yaw alignment, and operates efficiently at low cut-in wind speeds (1.5–2.5 m/s). It harvests natural breezes and forward-motion induced airflow.
- Dual-Input Power Conditioning & Storage: The 3-phase AC output of the micro-wind turbine is converted to DC via a low-drop Schottky diode bridge rectifier. A multi-channel Buck-Boost MPPT controller combines solar and wind DC lines through blocking diodes to charge a 12V 12Ah Lithium Iron Phosphate (LiFePO4) battery pack.
- Central Embedded Processor: An Arduino Mega 2560 / ESP32 microcontroller executes real-time obstacle avoidance algorithms, processes Bluetooth UART strings, monitors battery voltage dividers, and drives PWM motor controllers.
- Locomotion and Cutting Actuation: Dual high-torque 12V DC geared motors (60 RPM) powered via an L298N / BTS7960 motor driver enable differential steering. A dedicated 12V 4000 RPM high-speed DC motor directly drives the hardened steel rotary cutting blade with an active electronic braking relay.

3.2 Dual-Mode Operational Control Logic

The system operates in two distinct software-selectable modes managed via an Android smartphone Bluetooth interface:

- Mode 1 — Autonomous Obstacle Avoidance Mode: The robot navigates autonomously using a front-mounted tri-ultrasonic sensor array (Left, Center, Right). If an obstacle is detected within a threshold distance (< 25 cm), the blade continues rotating while the drive motors stop, reverse 15 cm, scan left and right angles, and steer into the clear trajectory with maximum clearance.
- Mode 2 — Manual Bluetooth Teleoperation Mode: The operator overrides autonomous routines via an Android application (paired via HC-05/BLE). Single-character ASCII commands control Forward, Reverse, Left, Right, Stop, and Blade ON/OFF states with real-time battery voltage monitoring displayed on the smartphone UI.

4.0. Conclusion

This literature review comprehensively analyzed the technological evolution, subsystem architectures, and performance constraints of modern autonomous lawn maintenance machinery. While the transition from fossil-fuel mowers to solar-powered robotic cutters has yielded immense environmental and operational benefits, pure solar systems remain critically constrained by environmental factors and intermittent sunlight. By synthesizing findings across 26 foundational and contemporary research studies including newly reviewed Bluetooth/IoT solar-cutter implementations and dedicated micro-wind rotor design studies

The proposed Hybrid Solar-Wind Powered Autonomous Grass Cutting Machine with Bluetooth teleoperation bridges critical gaps identified in the literature. Combining solar PV generation with omnidirectional micro-wind energy harvesting, multi-sensor ultrasonic obstacle detection, dual-mode control logic, and safe Bluetooth smartphone operation creates an energy-resilient, zero-emission, highly dependable autonomous machine tailored for modern sustainable landscaping.

Future advancements in hybrid autonomous grass cutters should explore the following frontiers:

- Computer Vision & Grass Classification: Integrating TinyML edge cameras (e.g., ESP32-CAM, Raspberry Pi Zero) to distinguish between healthy grass, bare soil, flowers, and foreign debris to achieve selective spot cutting.
- Self-Docking and Kinetic Regenerative Braking: Developing autonomous homing beacons allowing the hybrid robot to return to a solar-wind base station for rapid contact charging when battery state-of-charge (SoC) drops below 15%.
- Advanced SLAM Mapping: Employing solid-state 2D LiDAR to generate millimeter-accurate 2D occupancy grid maps of the lawn, eliminating boundary wire installation entirely.
- Chassis-Integrated Rotor Validation: Field-testing hybrid Savonius-Darrieus micro-VAWTs (per Paper 26) directly on a moving mowing chassis to quantify real-world gains from forward-motion-induced airflow, closing the gap between component-level rotor studies and robotic deployment.

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