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Review

A Review of the Performance of Smart Lawnmower Development: Theoretical and Practical Implications

Elwin Nesan Selvanesan [1], Kia Wai Liew [1,2,*], Chai Hua Tay [2,*], Jian Ai Yeow [3,4,*], Yu Jin Ng [5,6], Peng Lean Chong [7] and Chun Quan Kang [1]

[1] Faculty of Engineering and Technology, Multimedia University, Jalan Ayer Keroh Lama, Bukit Beruang, Melaka 75450, Malaysia; elwin.nesan.selvanesan@student.mmu.edu.my (E.N.S.); kangchunquan@gmail.com (C.Q.K.)
[2] Centre for Advanced Mechanical and Green Technology (CAMGT), CoE for Robotics and Sensing Technologies, Multimedia University, Jalan Ayer Keroh Lama, Bukit Beruang, Melaka 75450, Malaysia
[3] Centre for Management and Marketing Innovation (CMMI), CoE for Business Innovation and Communication, Multimedia University, Jalan Ayer Keroh Lama, Bukit Beruang, Melaka 75450, Malaysia
[4] Faculty of Business, Multimedia University, Jalan Ayer Keroh Lama, Bukit Beruang, Melaka 75450, Malaysia
[5] Faculty of Education and Humanities (FEH), UNITAR University College Kuala Lumpur (UUCKL), Jalan Perak, Wilayah Persekutuan, Kuala Lumpur 50450, Malaysia; yujin.ng@unitar.my
[6] Language Centre, Faculty of Education and Humanities (FEH), UNITAR International University, Jalan SS 6/3, Ss 6, Kelana Jaya, Petaling Jaya 47301, Malaysia
[7] School of Engineering and Computing, MILA University, No 1, MIU Boulevard, Putra Nilai, Nilai 71800, Malaysia; keith.chong@mila.edu.my
* Correspondence: kwliew@mmu.edu.my (K.W.L.); taychaihua@mmu.edu.my (C.H.T.); jayeow@mmu.edu.my (J.A.Y.)

Abstract: Smart lawnmowers are becoming increasingly integrated into daily life as their performance continues to improve. To ensure consistent advancement, it is important to conduct a comprehensive analysis of the performance of various modern smart lawnmowers. However, there appears to be a lack of thorough performance evaluation and analysis of their broader impact. This review explores the key performance indicators influencing smart lawnmower performance, particularly in navigation and obstacle avoidance, operational efficiency, and human–machine interaction (HMI). Key performance indicators identified for evaluation include operating time, Effective Field Capacity (FCe), and field efficiency (%). Additionally, it examines the theoretical and practical implications of smart lawnmower development. Smart lawnmowers have been found to contribute to advancements in machine learning algorithms and possibly swarm robotics. Environmental benefits, such as reduced emissions and noise pollution, were also highlighted in this review. Future research directions are discussed, both in the short and long term, to further optimize smart lawnmower performance. This review serves as a foundation for future studies and experimental investigations aimed at enhancing the real-world applicability of smart lawnmowers.

Keywords: smart lawnmower; performance; lawnmowing; theoretical implications; practical implications

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1. Introduction

Due to rapid advancements in information and communication systems, robots are becoming a vital part of social life in supporting domestic work. According to a recent study in 2023, nearly 40% of the time spent on domestic chores could be automated within a decade. This forecasted result is based on 17 common domestic tasks, which include

grocery shopping, household cleaning, and gardening [1]. In correlation with gardening, lawnmowing is an important urban legacy, with homeowners recognizing its importance for a variety of safe recreation activities, cooling the environment, and aesthetic benefits [2]. More than that, mowing also helps maintain soil quality and mitigate lawn pests [3].

Over the last couple of decades, lawnmowers have come a long way in terms of technology and innovation, resulting in various versions that can be categorized according to their power source: manual, traditional gas, and electrical, as shown in Table 1. Manual lawnmowing can be a tedious and time-consuming task for homeowners. According to the U.S. Bureau of Labor Statistics, manual labor in lawn and garden care can exceed 13 h per week [4]. A traditional gas-powered lawnmower offers less physical labor to operate but at a cost of significant noise pollution, greater than 85 decibels [5], which possibly causes hearing damage according to the World Health Organization [6]. This type of lawnmower also contributed to the elevated degrees of localized emissions, including carbon dioxide (CO_2) and criteria pollutants [7].

Table 1. General comparison of lawnmowers based on power sources.

Aspect	Manual Mower	Gas-Powered Mower	Electrical Mower		
			Corded	Battery Operated	Smart
Autonomy Level	Fully Manual	Partially Assisted	Partially Assisted	Partially Assisted	Fully Autonomous
Ease of Use	Very Demanding	Easy to Use	Moderately Easy	Easy to Use	Effortless
Noise Friendliness	Quiet	Very Noisy	Quiet	Quiet	Quietest
Eco-Friendliness	Emission-Free	Emits Pollutants	Emission-Free	Emission-Free	Emission-Free
Mobility	Unlimited Range	Unlimited Range	Cord-Limited	Battery-Limited	Unlimited Range
Ease of Maintenance	Minimal Upkeep	High Maintenance	Low Maintenance	Low Maintenance	Low Maintenance
Market Growth	Minimal Demand	Currently Dominant	Rapid Growth	Rapid Growth	Fastest Growing

Over time, electric lawnmowers have emerged, presenting a compelling alternative to addressing the noise and emission concerns, as well as the high maintenance associated with gas-powered models [8]. However, corded electric lawnmowers still require a significant human effort to operate. Additionally, its cord limits the operational range [9]. Naturally, this resulted in the emergence of battery-operated lawnmowers which offer lightweight simplicity and no dependency on conventional energy sources. Yet, two disadvantages are clear: the dependency on humans to operate and the limited battery life.

With the advancement of technology, smart lawnmowers have become increasingly popular due to their ability to mow lawns automatically without human intervention. In Italy, autonomous lawnmowers are appreciated for saving time and reducing physical effort, by allowing people to avoid tedious lawn care [10]. Recognizing the increasing interest in the smart lawnmower, its market is anticipated to grow at a Compound Annual Growth Rate (CAGR) of 10.9% from 2023 to 2030 [11]. This market is driven by the emergence of remote-controlled and Global Positioning System (GPS)-equipped autonomous lawnmowers, making gardening easier. There has also been a notable rise in consumer interest in gardening activities across the globe, creating an increased need for robotic lawnmowers [11]. Additionally, robotic lawnmowers are more environmentally friendly than gas-powered lawnmowers since they do not emit polluting gas while in use [12–15]. This is appealing to homeowners who are concerned about the environment [16]. These highlight the consumer demand for automation in lawn care and the rise in smart lawnmower development. Figure 1 displays the radar chart on various types of lawnmowers, highlighting the advantages of smart lawnmowers.

There has also been an increase in academic article publications on smart lawnmowers as displayed in Figure 2. It was found that both Google Scholar and Scopus displayed a steady 5-year increment in publications from 2000 to 2024. This is evident in the increase in smart lawnmower studies among academicians and researchers.

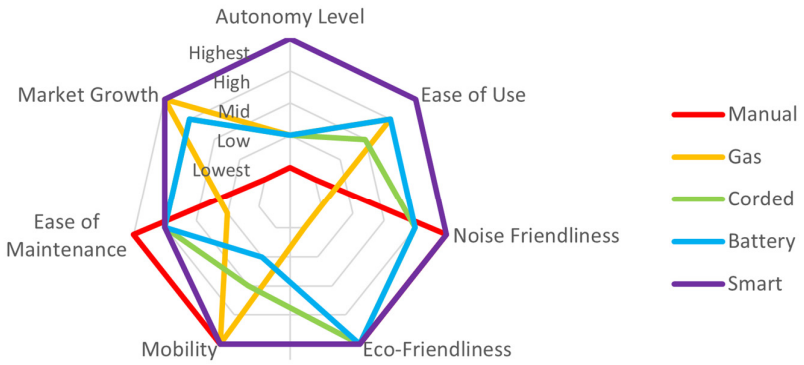


Figure 1. Radar chart on various types of lawnmowers based on power sources.

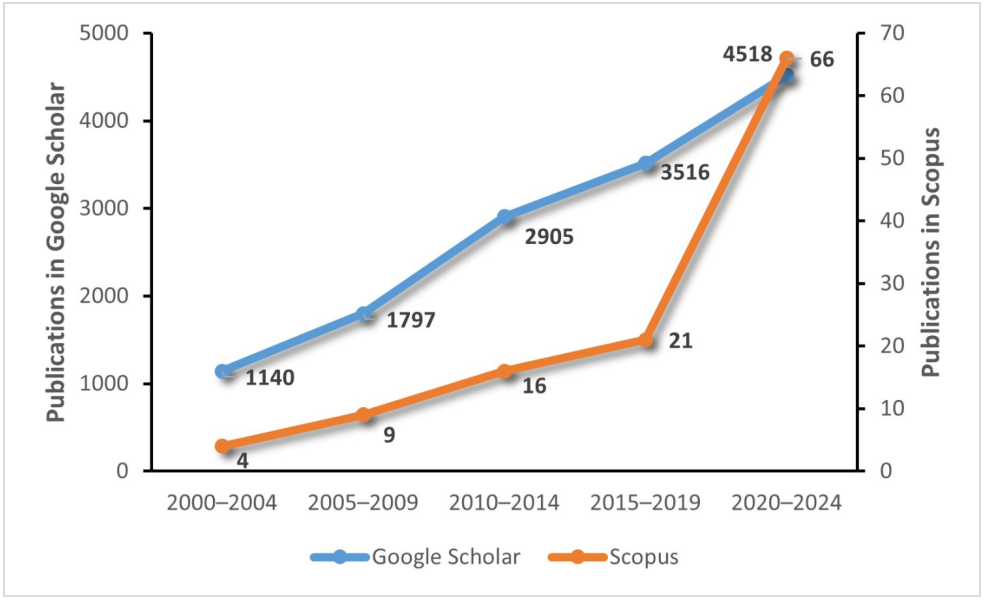


Figure 2. Publication trends on smart lawnmowers in Google Scholar and Scopus.

Despite the rapid development and increasing interest in smart lawnmowers, there is a lack of studies that provide a comprehensive review of their performance. Existing smart lawnmower reviews primarily focus on specific technologies rather than overall functionality. For instance, Pk and Patel (2023) focused on navigation algorithms, sensor technologies, and energy efficiency [17], while Shivbhakta et al. (2024) [18] examined the recent development in solar-powered lawnmowers. Though these studies provide valuable insights, they do not comprehensively analyze the theoretical and practical implications of the recent smart lawnmower's overall performance, particularly in aspects such as navigation and obstacle avoidance, battery life, energy efficiency, mowing quality, weather and terrain performance, human–machine interaction, environmental impact, prototype and design, operational efficiency, engine efficiency, and material selection. It is particularly important to fill this gap by providing measurable criteria as guidance for researchers to assess a smart lawnmower's efficiency and effectiveness. This review aims to fill that gap through a performance review by identifying the key performance indicators. Thus, the research questions (RQs) of this performance review article are as follows:

RQ1: What are the key performance indicators considering the use of smart lawnmowers?

RQ2: What are the theoretical and practical implications of developing smart lawnmowers in performance such as navigation and obstacle avoidance, battery life, energy efficiency, operational efficiency, and human–machine interaction?

2. Literature Analysis on Smart Lawnmower Performance

Numerous studies on the development of smart lawnmowers have been published, as previously shown in Figure 2. To provide a strong foundation for the theoretical and practical implications of smart lawnmowers, it is important to analyze the performance considered. This section analyzes the experimentation involved in the development of smart lawnmowers.

2.1. Navigation and Obstacle Avoidance

Navigation and obstacle avoidance play a crucial role in enabling smart lawnmowers to efficiently navigate and mow a given area. Commonly employed navigation systems are Light Detection and Ranging (LiDAR) sensors [19,20], GPS [21–24], and ultrasonic sensors [25,26], with their mechanisms widely reported. A less common system employed in smart lawnmowers is Simultaneous Localization and Mapping (SLAM), which allows the mower to build a map of its surroundings while simultaneously determining its position within that map using a LiDAR laser. This lawnmower design was created in SolidWorks, and then the Robot Operating System (ROS) and Gazebo were used to perform autonomous navigation. The ROS is a software library that aids in the development of robot applications. The robot would autonomously explore and map the virtual universe and construct a 2D representation of its spatial landscape. An effective navigation strategy was also implemented [20].

Additionally, path planning algorithms, such as A* or Dijkstra's algorithm, have been employed to generate optimal routes for the mower to cover the entire lawn while avoiding obstacles [27]. On the other hand, Höffmann et al. (2022) developed a concept for automatic path planning and high-precision localization for autonomous lawnmowers to contribute to the increased efficiency of the presented approach compared to classical automatic lawnmowing techniques [28]. In another experimental study of a smart lawnmower's navigation system, Okwu et al. (2022) [29] found that the Total Intelligent System (TIS) tested using fuzzy logic techniques was effective in navigating the lawnmower in a straight line and around an obstacle. Meanwhile, experimental studies by Duan et al. (2022) [30] and Balakrishna and Rajesh (2022) [31] found that using computer vision technology and the Internet of Things (IoT) for obstacle avoidance was also effective in navigating and mowing lawns without human intervention. In another study, Guo et al. (2021) [32] designed a fuzzy adaptive PID control algorithm of the mowing robot differential steering control system according to the domestic green environment and the overall parameters of the mowing robot. Aiming at the problem of inflexible steering and motion of the robot, the study focused on improving the mower's rapidity and accuracy. More navigation and algorithm systems includes the Beidou Navigation Satellite System [27] and Coverage Path Planning (CPP) algorithm [33], alongside their other smart features. Alternatively, smart lawnmowers can also incorporate sensor technologies that have been reported in mobile robotics [34] and thermal vision in lane detection [35] and traffic monitoring system studies [36].

2.2. Battery Life

Battery life is a critical aspect of smart lawnmowers, which dictates its runtime and overall user satisfaction. According to Hameem et al. (2020) [37], the battery life depends on the lawn conditions, grass density, moisture content, grass length, and height of cut. This was concurred by Balaji et al. (2021) [38], who reported on the battery life depending on the cutting area size. Switching the lawnmower on and off frequently during cutting will reduce the battery life. On the other hand, cutting more frequently, raising the cutting height, and operating at a normal pace will improve the battery life [37].

Hoda et al. (2024) [39] developed a smart solar grass cutter and displayed the mower's system in a flowchart as shown in Figure 3. The process starts with gathering solar energy and charging the battery. After initialization, the mower checks for obstacles using ultrasonic sensors and cuts grass until the entire region is covered. Most importantly, the system also incorporates a battery level check. When there is insufficient battery life, the mower either keeps charging or shuts off, depending on solar energy availability. However, when there is a sufficient battery life, the mower continues operating before powering down, either due to low battery or no more areas for grass cutting.



Figure 3. Flowchart of automatic lawnmower which incorporates battery management by Hoda et al. (2024) [39].

2.3. Energy Efficiency

Rahim and Johar (2021) [40] reported on the successful ability of smart lawnmower batteries to retain their energy until the end of the mowing mission. The study includes the analysis of several grid patterns (straight, cross, corridor, and spiral), covering the desired area for mowing. It was found that the straight grid is the best pattern to be adopted for its least estimated time taken to complete the mowing mission. This is because a straight grid pattern lowers the possibility of overturning, where the mower only takes several

short turns between the lines. Ultimately, this efficient energy system optimizes the battery usage, thereby prolonging the battery life.

Akinyemi et al. (2020) [41] fabricated and tested a solar-powered lawnmower. During operation, electrical energy from the battery was converted to mechanical energy through the blade. Additionally, the solar panel was continuously charging the battery during operation. The efficiency of the solar lawnmower designed and developed is 85%, where it takes 5 h for the battery to charge, allowing it to operate for 50 min. The reason for the short working duration of the battery is due to the high current draw of the electric motor. Nevertheless, the ability for the battery to charge throughout the operation, as long as the sun shone on the surface of the solar panel, offers efficient energy management worth mentioning.

2.4. Mowing Quality

The quality of lawnmowing is another critical aspect of smart lawnmowers. Moore (1997) [42] mentioned that the evaluation of a lawnmower's performance often revolves around assessing the visual quality and aesthetic appeal of the grass after it has been cut. In theory, every blade of grass should be clipped to the same height. The extent of achieving such an outcome with an existing mower and blade design depends on a variety of factors, including grass type, starting grass height, moisture (density), lawnmower forward velocity, and how well clippings are released from the mower. Other variables, including poor airflow and the fact that the front tire of the tractor compacts the grass into the ground before the mower blade goes over, are known to degrade performance. All of these variables might lead to areas of grass that are not trimmed or are mowed excessively short. Despite Moore's article being published around three decades ago, Moore provided a concrete evaluation for the development of lawnmower performance.

Daniyan et al. (2020) [23] designed, fabricated, and evaluated the performance of a prototyped robotic lawnmower. The electrical circuit connections between the microcontroller and the rest of the electrical system were designed with the aim of producing a system that can cut grass at high efficiency with little or no human intervention. The mower was incorporated with the GPS, cameras, and infrared and ultrasonic sensors for the detection and avoidance of obstacles. A performance evaluation revealed that the developed lawnmower can follow a well-predetermined path and autonomously make decisions regarding path planning. The mower can turn approximately 180° to avoid obstacles and cut a lawn to an even height with high cutting efficiency. Typical, even cut, and clean mowing lines, which characterize an aesthetically manicured lawn, were obtained for the different lawns with different grass types.

Pirchio et al. (2018) [43] compared the effects of autonomous mowing and gasoline-powered rotary mowing on turf grass quality. The autonomous mower operates by 420 sets, 8 h per day, while the gasoline mower is operated by a human and mows once a week, covering six subplots with a size of 234 m^2 each. It was found that the autonomous mower can increase turf quality compared with the gasoline-powered one. According to the authors, this could be due to the high cutting frequency of the autonomous mower which led to a constant and lower average turf height.

Tanaji et al. (2018) [44] carried out a field test, utilizing not just one but four types of grass, which are elephant grass, stubborn grass, spare grass, and carpet grass, where the average heights of the grass before mowing were 230 mm, 234 mm, 111 mm, and 70.5 mm, respectively. The expected heights of the grass after mowing for elephant grass, stubborn grass, and space grass were 90 mm, 90 mm, and 80 mm. However, after mowing, the average heights of the grass following the same sequence were 80 mm, 84 mm, and 80 mm. No result was reported for the carpet grass. The difference between the average grass

height and the expected height after mowing is low, but no reason was provided for the result. The efficiency of the machine was concluded to be 90%.

Magar et al. (2010) [45], Nkakini and Yabefa (2014) [46], and Kulhariya et al. (2020) [47] conducted a field test on plots of 20 m × 10 m and 4 m × 2 m areas covered with carpet grass (Axonopus Affinis) and plots of 20 m × 50 m areas covered with stubborn grass and spare grass. The median grass height after the cut was found to be 100 mm. It was also found that the height of the cut grass did not vary with the height of the grass before it was cut. The height remained constant since the grass cutting blades were non-adjustable. The operational speed completely relied on the lawnmower's speed and intensity. It was found that the speed of the operation diminished with the density of the grass in the area. The machine demonstrated higher effectiveness when operating under dry soil conditions, attributed to its ability to maintain an adequate tire grip on such surfaces. Meanwhile, the field efficiency was found to decrease as the operating speed increased. However, in the case of Nkakini and Yabefa (2014), it was found that field efficiency increased with the operating time [46].

During an experiment to cut four trials of grass with varying initial heights, Rajmani et al. (2019) [48] noticed that the average height of the grass after mowing was more than the projected height after the machine was used for cutting. The machine's efficiency was determined to be at 92%, and the Effective Field Capacity was 1.11×10^{-4} ha/h. While more proof is required, there is a possibility that the reduction in the cut grass height may be due to the toughness, density, and resilience of stubborn grass. In addition, continually switching the lawnmower on and off during the mowing process could also diminish the battery life. This lawnmower, designed by Rajmani et al. (2019), is displayed in Figure 4.

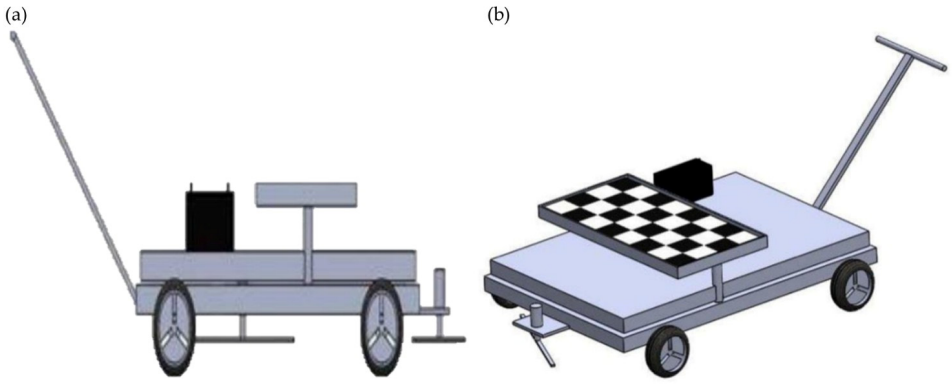


Figure 4. (**a**) Side view showing the placement of blades and (**b**) an isometric view of the lawnmower [48].

In trimming the grass, Foong and Ismail (2019) [49] conducted research to assess the intensity of vibration and sound at various wedge angles of the blade. The experiment used the typical Malaysian grass known as cow grass. The cow grass used was new, healthy, and devoid of mechanical damage. The grass was chopped through by the blade with a variable angle and using a high-speed DC-geared motor. However, based on the experiment, increasing the wedge angle seemed to increase the level of vibration and sound.

2.5. Weather and Terrain Performance

Unlike manual mowing, which can be interrupted by inconsistent weather, smart lawnmowers are capable of adjusting their behavior based on the weather. This is due to weather monitoring devices such as temperature, rain, or humidity sensors that could be integrated into the lawnmower control system (Onuabuchi et al., 2024) [50]. In addition

to this, implementing weather prediction technology enables the lawnmower to adjust its schedule based on upcoming weather conditions. This could include avoiding mowing during heavy rain, adjusting cutting height based on humidity, or responding to temperature changes (Santhoshini et al., 2024) [51]. Despite that, it is clear that the solar-based lawnmower has power constraints, limited by its energy harvesting capabilities (Adeboye et al., 2025) [52]. Nevertheless, according to Dada and Popoola (2023) [53], modern solar panels are more stable and durable than earlier versions. They can now withstand extreme temperatures and harsh weather conditions, making them suitable for use in a wide range of environments.

Smart lawnmowers can also adapt to various lawn conditions, terrains, and grass types, making them highly versatile and effective across different environments (Sawant et al., 2024) [54]. Fineas and Sever-Gabriel (2022) [55] conducted a comparative study among four smart lawnmower models available in the market. Two of the models, Robot 1 and Robot 2, were reported to have no issues operating in all weather conditions, whether wet or rainy. Additionally, Robot 1 can perform in difficult terrain, including slopes, potholes, and even temporary obstacles such as cones and fruits. On the other hand, Robot 2 can operate on slopes with a 27% gradient. However, Robot 3 and Robot 4 were not discussed in terms of performance in varied weather, but have no issue operating in uneven terrain with slopes.

Derander et al. (2018) [56] reviewed and tested the general performance of their lawnmower prototype. The prototype's velocity was roughly 0.2 m/s when measured on levelled grass. This velocity, however, was measured in a continuous forward motion and did not include a start and finish point. On the grass, the prototype's maximum inclination was estimated to be around 12°. However, a greater incline would cause the prototype's wheels to lose traction and overturn. The battery time was determined to be 3 h after testing it for a period of time. This study suggests that homeowners should select smart lawnmowers with weather-resistant features and adaptability in various terrains for optimal performance.

2.6. Human–Machine Interaction

Human–machine interaction models are essential for ensuring safe and effective collaboration between the user and the smart lawnmower. These models focus on intuitive control interfaces, obstacle detection, and emergency stop mechanisms to enhance user experience and prevent accidents. Additionally, research into user preferences, trust, and acceptance of smart lawnmowers can inform the design of human-centered systems. Siregar, Hutagaol, and Sitompul (2020) [57] placed their smartphone-controlled lawnmower robot through a series of tests to confirm its functionality. Command input testing, actuator testing, autonomous mode testing, robot movement testing, trimmer function testing, and ultrasonic sensor testing were all performed on this system. Mechanical testing scenarios were run on two types of terrain (grass-field area; hilly and hollow contours). Robot motions such as forward, backward, left, right, autonomous motion, and ultrasonic sensor functions were successfully employed on the grass-field region, which had flat land features. However, the robot had trouble traveling forward and backward in other areas with hilly and hollow contours. The sensor was also incapable of detecting an obstruction in the form of a hole beneath the robot. Trimmer testing was performed on two distinct types of grass. The trimmers exhibited excellent cutting capabilities, particularly in softer grass varieties, resulting in a neat and well-maintained appearance. However, when faced with stubborn grass, the trimmers proved ineffective in achieving a clean cut. Aside from Siregar, Hutagaol, and Sitompul (2020) [57], many researchers have also reported on the HMI function of their smart lawnmowers [20,21,23,24].

2.7. Environmental Impact

Solar-based smart lawnmowers are known for their environmental friendliness as they do not emit any harmful gases or pollutants during operation. However, to accurately assess the environmental impact of the smart lawnmower, it is important to conduct its Life Cycle Assessment (LCA). Saidani et al. (2020) [58] published a comprehensive assessment on the environmental sustainability of an autonomous system for the agricultural industry, the robotic lawnmower. Comparative LCA was carried out on a real-world case study, comparing a robotic lawnmower, gasoline-powered lawnmower, and electric-powered lawnmower. The first assessment involved the required mowing time with respect to the functional unit. This is important as reduced mowing time directly lowers the energy consumption, battery usage, and the wear of lawnmower components such as the blades and motor. As such, for smart lawnmowers, which often operate in random navigation mode, minimizing mowing time can significantly contribute to environmental sustainability. Current robotic lawnmowers require 20 h per week to properly cover a 0.25-acre rectangular field. On the other hand, using optimal path planning (as a human would naturally mow the field) would only take 4 h per week. The second assessment involved the Global Warming Potential (GWP) associated with manufacturing, usage, and maintenance phases for each mower, as displayed in Figure 5. The current version of the robotic mower, which requires 20 h per week, is 23% greener than a conventional gasoline-powered push mower. The environmental savings could be significantly higher (lower electricity consumption and fewer battery replacements) by reducing the mowing time. For instance, the 0.5 metric ton of CO_2 emissions could be avoided by replacing one gasoline-powered push mower with a robotic mower that has optimal path planning (2 h and 30 min per week). This suggests that lawn owners can make an even more environmentally sustainable choice by selecting a smart lawnmower equipped with optimal path planning.

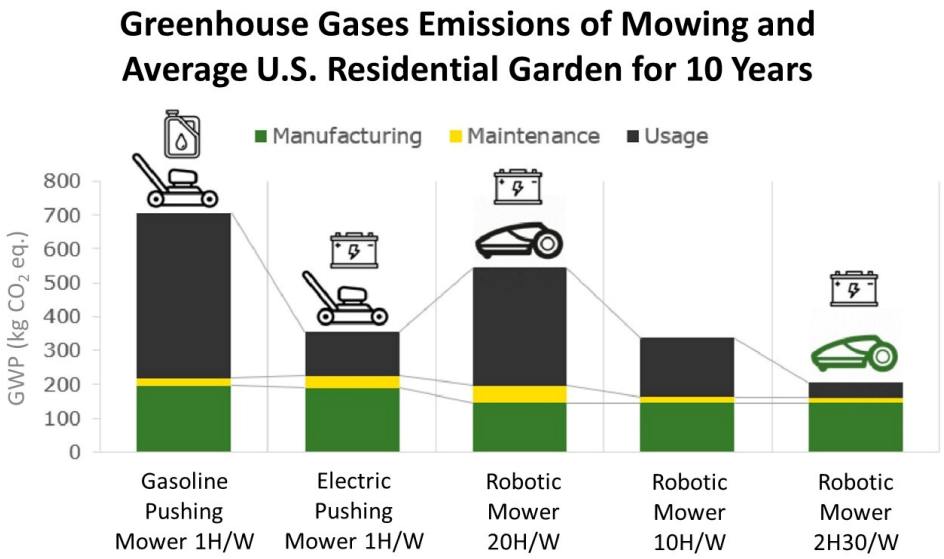


Figure 5. Quantitative results of the greenhouse gas emissions of mowing [58].

2.8. Prototype and Design

On the topic of designing the lawnmower, changes were most often required during the fabrication stage of a product to optimize its performance. Hence, the initial design of the prototype should be made flexible to allow for future changes. For this purpose, a method such as the Theory of Inventive Problem Solving (TRIZ) could be used [59]. TRIZ is a common approach to problem solving in engineering [60]. Also, the design of a smart lawnmower can be synthesized from patents, journals, and products for better

conceptualization before fabrication, as carried out by Lim and Ng (2016) for their product development [61].

Cochrum et al. (2014) [62] developed an overall system design for an autonomous lawnmower comprising four elements that are in direct connection with one another. These elements include position mapping, driving and orientation, avoiding obstacles, and path calculation. Each of these subsystems consisted of sensors and parts that interact with one another via a centralized processing unit. These subsystems collaborate to form the autonomous system. This lawnmower's performance was evaluated through tests. The lawnmower's route was established by locating the next node to be mowed along the intended path. However, throughout the testing, the compass experienced serious accuracy concerns, resulting in potentially inaccurate findings.

Hossain and Komatsuzaki (2021) [63] conducted a case study to compare the mowing cost (annual ownership, repair and maintenance, energy, oil, and labor) of a riding mower, brush cutter, and walking mower against that of a robotic lawnmower (RLM) for operation in a pear orchard. During fruit-thinning times, the RLM encountered vibration issues when traversing small pears measuring approximately 33 $\pm$ 8 mm in diameter. These vibrations caused the blade movement to come to a halt. Throughout the process of pear harvesting, the RLM frequently experienced interruptions as dropped fruits with a diameter of approximately 80 $\pm$ 12 mm collided with the blade and became lodged within the machine's chassis. These occurrences led to frequent halts in operation.

Kang et al. (2021) [7] made a conceptual synthesis of a smart lawnmower and fabricated a prototype. The lawnmower had several noteworthy features, including solar-powered operation, multifunctionality (lawnmowing and floor polishing), dual operation mode, and the ability to achieve an optimized grass-cutting height. Two-sample *t*-tests were used to analyze the sound intensity and cutting ability. Observations, mean comparisons, and manual calculations were used to analyze the data from the polishing performance and battery power durability tests. However, these experiments were performed only on one type of grass and on level grassland. Furthermore, in terms of functionality, the lawnmower encountered challenges when navigating uneven terrains, leading to instances where it could tip over or become trapped. It also had a slow response time when it changed trajectory. There was no emergency stop button, and the finished product was often untidy due to the thick grass blades left behind. The material was made of wood, which was not aesthetically pleasing for commercial transition purposes. Although the wheels were functional, they were also flimsy and lacked the grip or friction needed for more slippery terrain.

Nevertheless, in a subsequent research paper, Kang et al. (2022) [64] conceptualized an improved lawnmower that has been prototyped. The improved version includes stress simulation and product optimization using modelling and simulation software such as the Autodesk Inventor (version 2019) and ANSYS (version 2019 R2). This approach ensured that the lawnmower is materially efficient and not over-engineered.

2.9. Operational Efficiency

Operational efficiency models are employed to optimize the mowing process and reduce energy consumption. For instance, predictive models can take into account factors like grass growth rate, historical data, and weather conditions to determine the most efficient schedule for mowing. For example, Sasikumar et al. (2024) [13] employed intelligent automation enabled by IoT technology, which allows for adjusting schedules based on real-time weather conditions. This smart feature helps conserve energy by ensuring that the mower operates only when necessary while keeping the lawn well maintained.

On the other hand, for smart lawnmowers that depend on electricity, the ability to autonomously return to a charging station when the battery level is low is an important feature for operational efficiency [21]. This feature prevents the lawnmower from stopping in the middle of an operation due to a low battery, ensuring continuous operation and task completion in time. As such, this reduces human intervention, as there is no need to manually monitor the battery level. Overall, this contributes to the improved energy utilization of a smart lawnmower.

Additionally, the lawnmowers developed by Nisari et al. (2021) [65] provide a user interface to tailor operations specific to lawn conditions. This includes configuring the lawnmower movement and speed of cutting grass, allowing user customization for tailoring mowing strategies based on lawn size and grass type. Similarly, the Bluetooth-controlled lawnmower by Aditya et al. (2024) [66] also offers a user interface, allowing users to monitor the cutting progress remotely and ensure precise operation.

2.10. Engine Efficiency

Aside from the aforementioned performance, engine efficiency is also an important aspect to be discussed for smart lawnmowers. Engine efficiency can be evaluated by inspecting the relationship between charging time and operating time. An efficient engine can operate for long hours while requiring a short charging period, indicating good energy conversion from storage to mechanical work. For instance, Pirchio et al. (2018) [43] developed a smart lawnmower that requires only 2.7 h of charging, which allows for it to operate for 5.3 h. On the other hand, solar-based smart lawnmowers have been reported by Manikandababu et al. (2024) [19] to require 6 h of charging. Despite the longer charging period, a solar-powered system offers advantages in sustainability and free renewable energy. Bhanu Sri et al. (2024) [22] also reported on 6 h of charging through solar power, resulting in 1 h of operating time. Raza et al. (2023) [25] on the other hand, published their solar-powered smart lawnmower that requires a short charging period of only 3 h, which allows for a longer operating time of 2.8 h. While the utilization of solar power is good for smart lawnmowers, the reliance on the availability sunlight highlights the more stable charging for electric models. Several lawnmower concepts and prototypes were developed to run on electricity, supplemented by solar power, as reported by Daniyan et al. (2020) [23], Kang et al. (2022) [64], Premarathne et al. (2024) [33], Baluprithviraj et al. (2022) [67], and Nisari et al. (2021) [65]. This feature offers flexibility in practicing sustainability while offering practicality to weather and power source availability.

Khillare et al. (2020) [68] tested their fully automated solar grass cutter with experiments throughout the day, beginning at 11 am, for 5 h on flat and smooth grass. The lawnmower was evaluated on a standard lawn using the following parameters throughout the test period: area coverage, lawn availability, energy consumption, and machine intervention. When compared to its manual mode, the lawnmower's autonomous operation was more efficient in mowing the lawn and reduced the cutting time by around 57%.

Tunmise et al. (2022) [69] conducted research to investigate the influence of time and portion cut on machine efficiency under various conditions of cutting stubborn and soft grasses. It was found that there was a proportional gain in machine efficiency, as well as an increase in area cut for both stubborn and soft grasses. In addition, the machine's efficiency improved, with less cutting time required for both stubborn and soft grasses. The research suggested that increasing the area cut enhanced the system's efficiency. The machine's performance study also revealed that the lawnmower was light in comparison to traditional models. In contrast, the lawnmower's battery exhibited a shorter duration and slower charging compared to standard batteries.

2.11. Material Selection

The materials used in the construction of a smart lawnmower play a vital role in optimizing its efficiency, durability, and environmental sustainability. A key focus is to select materials that reduce weight and therefore energy consumption, while at the same time have the ability to extend durability under harsh conditions. Expanding on its durability, the material must be able to withstand buckling and bending loads to a certain extent with minimal density [7]. Kang et al. (2022) [7] selected the lightweight wood for the development of their conceptual lawnmower. Later, in a more refined conceptual design integrating TRIZ, Kang et al. (2022) [64] mentioned that lightweight materials can also reduce the frequency of lawnmower charging. This can be achieved through the use of porous materials. Okwu et al. (2022) [29] specifically focused on the development of a lightweight lawnmower. For this purpose, the chassis was fabricated using a PCV pipe and plywood; the clearing mechanisms, which include the DC motor, cutting blade, blade frame, bold and nut, were produced from aluminum, the gripper was made of acrylic, while for powering the system, lithium batteries were used.

As lawnmower technology advances, so does the potential for better materials in its structure. One promising material is the Natural Fiber Reinforced Polymer (NFRP), which could replace the traditional lawnmower materials. NFRPs are composites where natural fibers such as banana [70], betelnut [71], kenaf [72,73], jute [74], and flax [75] are used as reinforcements within the polymer. Natural fibers are biodegradable and are extracted from renewable resources, contributing to their environmentally friendly traits. Additionally, the properties of NFRP can be customized by adjusting the type of natural fiber, ratio of natural fiber, and through the introduction of nanoparticles, reinforcements such as mesoporous silica [76], graphene [77], CNT [78], and nanoclay [79]. Thus, manufacturers have the freedom to tailor the properties of NFRP to meet the specific performance required of the lawnmowers. The potential of such composites has already been demonstrated in the automotive sector, where NFRPs have been successfully used in BMW vehicles [80]. Figure 6 displays the laminate pieces of bamboo-reinforced polymer composites with curved geometries, proving the possibility of producing such a structure, which is significant for wider applications [81].

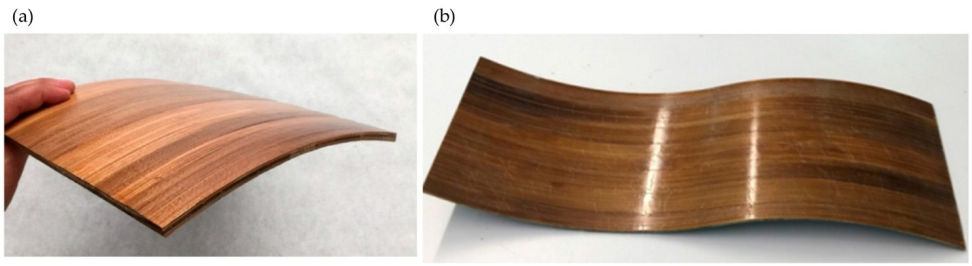


Figure 6. Demonstration panels manufactured from bamboo-reinforced polylactic acid composite in (**a**) cylinder concave shape and (**b**) concave and convex shape [81].

Alternatively, protective coatings can be applied to enhance the durability of existing materials used in lawnmower construction, particularly wood, which performs well in most aspects but lacks waterproofing. A polyurethane coating derived from peanut oil, as developed by Raychura et al. (2018) [82], could offer a sustainable solution. When applied to wood panels, this polyurethane showed comparable hardness and thermal stability to commercial coatings while demonstrating superior water repellence. Overall, this peanut oil-based polyurethane has the potential to replace petroleum-based coatings, providing an environmentally friendly protective layer for lawnmower components. Utilizing bio-based coatings like this provides an affordable solution for protecting lawnmower construction

materials without the need to replace the existing materials. Table 2 displays a summary of smart lawnmowers' performances by selected articles published mostly from 2020 to 2025. This table may serve as a quick reference for researchers to identify the methods used in previous smart lawnmowers studies.

Table 2. Summary of smart lawnmowers' performances by selected articles published between 2020 and 2025.

Navigation and Obstacle Avoidance		Engine Efficiency			Operational Efficiency	Human–Machine Interaction		Ref.
Navigation System	**Obstacle Avoidance System**	**Power Source**	**Charging Time (hours)**	**Operating Time (hours)**	**Optimization of Energy through Smart Features**	**Remote Control Capability**	**Safety System**	
LiDAR, cameras, ultrasonic sensors, and wheel encoders	Ultrasonic sensors	Solar	6		Maximum Power Point Tracking (MPPT) algorithms, which maximize solar panel energy collection.			[19]
LiDAR sensor with Robot Operating System (ROS), Simultaneous Localization and Mapping (SLAM)	LiDAR sensors and Inertial Measurement Unit (IMU)						Mower blade is designed to slide inside when mower is turned off.	[20]
GPS and ultrasonic sensors	Ultrasonic sensors	Solar			Autonomously return to its self-charging station when battery levels are low, and the integration of IoT technology for real-time monitoring and decision-making.	Mobile app or Web app		[21]
GPS, cameras, IR Sensors, and ultrasonic sensors	Infrared sensors and ultrasonic sensors	Electrical and solar				Mobile app		[23]
GPS	Heat and thermal sensors	Electric				Android App through Wi-Fi	Heat and thermal sensor, emergency stop function through app,	[24]
Ultrasonic sensors	Ultrasonic sensors	Solar	3	2.8	Arduino microcontroller and the zig-zag movement algorithm		nylon strings for cutting	[25]
Ultrasonic sensors	Ultrasonic sensors	Solar			Battery Management System (BMS)	Mobile app through Bluetooth		[26]
Beidou Navigation Satellite System, inertial navigation technology, and various sensors, including laser radar and cameras	Laser radar and cameras	Electric		1.5				[27]
RTK-augmented GNSS with inertial navigation system (INS)								[28]
Ultrasonic sensor	IR sensor and PSI	Electric		1.45	Atmega 328 microcontroller	Mobile app	PSI for human avoidance	[29]
Cameras	Computer vision technology and simplified convolutional neural network (CNN)							[30]
Ultrasonic sensors	Ultrasonic sensors					Blynk app		[31]
Coverage Path Planning (CPP) algorithm	Ultrasonic sensors	Solar supple-mented by electric			Solar panels			[33]
	Proximity sensor	Electric				Mobile app through Bluetooth		[38]
GPS (Ardupilot Mission Planner)	Sensors							[40]
GPS	Boundary wire		2.7	5.3				[43]

Table 2. *Cont.*

Navigation and Obstacle Avoidance		Engine Efficiency			Operational Efficiency	Human–Machine Interaction		Ref.
Navigation System	**Obstacle Avoidance System**	**Power Source**	**Charging Time (hours)**	**Operating Time (hours)**	**Optimization of Energy through Smart Features**	**Remote Control Capability**	**Safety System**	
Ultrasonic sensor	Ultrasonic Sensor				Intelligent navigation and obstacle avoidance	Mobile app	Auto shut-off when the mower is lifted	[51]
Ultrasonic sensor	Ultrasonic sensor	Electric				Mobile app through Bluetooth		[57]
Perimeter wire and ultrasonic sensors	Ultrasonic sensors	Electric supplemented by solar			Lightweight design and solar panels		Auto shut-off when the mower is lifted	[64]
Ultrasonic sensors	Ultrasonic sensors	Solar and electric			Users can tailor operations to specific lawn conditions	Bluetooth controller		[65]
ESP32 camera module		Solar			Users can tailor operations to specific lawn conditions	Mobile app		[66]
Cameras	Cameras	Solar and electric				Mobile app	Prevents the blades from operating when the mower is lifted	[67]
Ultrasonic sensor						App using IoT		[83]
Gyroscope sensor	Gyroscope sensor						The system stops when an obstacle is detected	[84]
Ultrasonic sensor	Ultrasonic sensor						Auto shut-off when the mower is lifted or touches a hard surface	[85]
Cameras	Cameras					Phython and Tkinter	human body infrared sensor, emergency stop button on the human–machine interface	[86]
Ultrasonic sensors	Ultrasonic sensors and PIR sensors		7.8			Mobile app through Bluetooth		[87]
Ultrasonic sensors	Ultrasonic sensors	Solar				Web app		[88]
Camera	Ultrasonic sensor	Solar				Mobile app		[89]
GPS and ultrasonic sensors	Ultrasonic sensors and a Pi camera	Electric				Mobile app		[90]
Ultrasonic sensors	Ultrasonic sensors	Electric				Mobile app	Limit switch crash sensor	[91]
Ultrasonic sensors	Ultrasonic sensors					Mobile app		[92]
A combination of sensors					IoT technology for real-time monitoring and decision-making	IoT		[93]
Ultrasonic sensors	Ultrasonic sensors	Electric					Automatic stop feature	[94]
Ultrasonic sensors	Three ultrasonic sensors and Two infrared (IR) proximity sensors				Fuzzy logic control			[95]

3. Discussion

3.1. Key Performance Indicators

Based on the literature analysis on smart lawnmower performance in Section 2, several key performance indicators were identified. These indicators were consistently reported across multiple, recently published studies, focusing on the development and performance

of smart lawnmowers. Their recurrence suggests the significance and relevance of benchmarking across various lawnmower designs and systems. These indicators can also provide measurable and comparable criteria as guidance for researchers to assess the efficiency and effectiveness of their smart lawnmowers. Speed, which includes operational speed, traveling speed, forward velocity, cutting speed, and blade speed, is one indicator that can be a comparable measurement for smart lawnmowers. In addition to this, operating time, FCe, and field efficiency (%) were often reported, making it a key performance indicator that can be easily compared during the development of smart lawnmowers. Additionally, it was found that parameters such as grass type, initial grass height, moisture (density), and labor involvement were often discussed as well.

3.2. Theoretical Implications

The development and experimentation of a smart lawnmower have several theoretical implications that can advance the fields of robotics and artificial intelligence (AI). Smart lawnmowers can serve as a platform for the development and testing of new algorithms, sensors, and communication systems. These devices require sophisticated algorithms to navigate and mow the lawn autonomously, which can lead to the development of more advanced machine learning algorithms that can be applied to other fields, such as self-driving cars and industrial robotics.

Another theoretical implication concerning the development of smart lawnmowers involves the advancement of swarm robotics. Swarm robotics has been widely explored in agricultural applications to facilitate a range of tasks such as crop monitoring, planting, precision farming [96,97], weed control, pest management, harvesting, pollination, and livestock management [97]. To date, there is limited research that addresses the use of swarm robotics specifically in autonomous lawnmowing.

One notable study was published by Inami et al. (2024) [98], which simulated a swarm of smart lawnmowers collaboratively, operating a total area of 31,730 m^2. The traveling speed of the lawnmower is set to 0.55 m/s when it travels on the lawn field with long grass and set to 1.0 m/s when it travels on the mowed lawn field. When compared to a simple mower, it was found that the simulated swarm lawnmowers achieved a reduction of 27% in traveling time, from 230 h to 168 h. This recently published work may encourage further research into the application of swarm robotics for lawn care. In turn, such research could contribute to the broader development of swarm robotic technologies for other applications such as environmental monitoring, defense and surveillance, search and rescue, construction and manufacturing, and even space exploration.

The development and experimentation with smart lawnmowers can also lead to the development of more sophisticated sensors and communication systems. Smart lawnmowers use a variety of sensors to navigate and mow the lawn, and they communicate with other devices and systems to provide updates on their progress. The experiments with these devices can lead to the development of new sensors and communication protocols that can be applied to other areas of robotics and AI. These algorithms enable the smart lawnmower to efficiently navigate and mow the lawn while considering obstacles commonly found in residential areas, such as trees, flowerbeds, or children's play equipment. These experiments could help explore optimal navigation strategies that ensure complete coverage of the lawn, minimize the need for manual intervention, and improve overall mowing efficiency.

In terms of HMI, which can be by means of voice, touch, or gesture (Cannan and Hu, 2011) [99], effective HMI in both contexts of lawn care and agriculture would require careful attention to ergonomics, including safety, usability, and a deep understanding of the specific needs and requirements of lawn care and agricultural operations. For example,

the process of starting and stopping a lawnmower includes interacting with the machine controls and safety features. In agriculture, the use of the GPS and other advanced technologies can help optimize the mowing process and improve efficiency. This may involve interacting with digital interfaces to set up and manage mowing routes, track progress, and monitor machine health and performance. In a residential setting, the lawnmower can avoid collisions and operate safely in the presence of objects or people. Investigations into human–machine interaction models are also important to ensure effective communication and collaboration between homeowners and the smart lawnmower, enhancing safety and usability.

Additionally, as smart lawnmowers become more widely used, they have the potential to reduce the amount of time and resources needed for lawn maintenance, which can contribute to more sustainable land use practices. One of the primary ways that smart lawnmowers save time and resources is through their ability to autonomously navigate and mow the lawn. Smart lawnmowers use sensors and mapping technology to identify the areas that require mowing and then autonomously navigate around the lawn to ensure that every area is covered. This automation eliminates the need for manual labor, saving time and reducing the resources needed for lawn maintenance. This precise approach to lawn maintenance also reduces the amount of soil disturbance and erosion caused by traditional mowers. As a result, the soil is better able to retain water and nutrients, which promotes healthy plant growth and helps to prevent soil erosion.

In addition to their automated lawn maintenance capabilities, smart lawnmowers are also highly efficient in their lawn coverage. By using sensors and mapping technology, they can precisely identify the areas that require mowing and then target those areas with precision. This efficient coverage reduces the amount of time and resources needed for lawn maintenance, making it a more sustainable and efficient process. Overall, the development of smart lawnmowers has significant theoretical implications for the future of robotics and AI.

3.3. Practical Implications

Smart lawnmowers are an innovative solution to a mundane task that can be time-consuming for homeowners. These devices use advanced technology to mow lawns with minimal human intervention, providing a convenient way to keep the lawn looking neat and well maintained. One of the most significant practical implications of smart lawnmowers is the time savings they offer. Homeowners who use these devices can reclaim the time they would have spent mowing their lawns and use it for other activities.

Another practical implication of smart lawnmowers is their environmental benefits. Firstly, one of the significant environmental advantages of smart solar-powered lawnmowers is the reduction in greenhouse gas emissions. Unlike gasoline-powered lawnmowers that emit carbon dioxide (CO_2) and contribute to climate change, smart lawnmowers do not produce direct emissions during operation. By relying on clean solar energy as their power source, they help mitigate the impact of greenhouse gas emissions on the environment.

In addition, smart lawnmowers contribute to decreased air and noise pollution. Operating silently and without exhaust fumes, they create a quieter and healthier environment, particularly in residential areas or parks where noise and air quality are of concern. By eliminating the noise and emissions associated with traditional lawnmowers, solar-powered alternatives provide a more pleasant and sustainable mowing experience.

Furthermore, the utilization of renewable energy is a key advantage of smart lawnmowers. By harnessing solar power, they reduce dependence on non-renewable fossil fuels. This promotes a more sustainable energy mix and contributes to the global transition to

a low-carbon economy. Solar-powered lawnmowers align with the goal of reducing the reliance on finite resources and embracing clean, renewable energy sources.

Another benefit is the lower energy consumption of smart solar-powered lawnmowers. These smart lawnmowers typically incorporate efficient motors designed to maximize energy conversion from solar panels. As a result, they consume less energy compared to electric lawnmowers powered by grid electricity, which may be generated from non-renewable sources. The reduced energy consumption of solar-powered lawnmowers contributes to overall energy conservation and efficiency.

Moreover, smart solar-powered lawnmowers operate independently of the electrical grid. They do not require an external power source, reducing strain on energy infrastructure and offering greater flexibility in remote or off-grid locations. This self-sufficiency minimizes the reliance on external energy sources and allows for the use of solar power even in areas with limited access to electricity.

Smart lawnmowers also have the potential to improve the overall health and appearance of lawns. These devices are equipped with advanced sensors and software that enable them to adjust their mowing patterns based on the condition of the grass. For example, if the grass is particularly long or thick in certain areas, the smart lawnmower may adjust its mowing pattern to ensure that those areas are cut more thoroughly. This can lead to more consistent growth patterns and a more uniform appearance.

Finally, smart lawnmowers offer a higher level of convenience and control for homeowners. These devices can be controlled and programmed using a smartphone app, allowing homeowners to set a schedule for when the lawnmower should mow the lawn and adjust settings like mowing height and frequency. This level of control and automation can make it easier for homeowners to maintain their lawns without having to dedicate a significant amount of time or effort. Overall, the practical implications of smart lawnmower development are significant and offer numerous benefits for homeowners who are looking for an easier, more efficient way to maintain their lawns.

3.4. Cost Analysis

While many studies have published the performance of smart lawnmowers in aspects such as navigation and algorithms, operational efficiency, and human–machine interaction, cost remains an underexplored discussion. However, cost or product pricing highly impacts a buyer's decision process. According to Zhao et al. (2021) [100], based on questionnaire data collected from 500 students, analyzed through confirmatory factor analysis, path analysis, and discriminant validity in structural equation modelling, it was revealed that product pricing has a statistically significant relationship with the buyer's decision process. In fact, product pricing is found to be more critical and relevant to the buyer's decision process than other factors like product packaging or product description information. This is why it is logical that the selection of material for the whole structure of a lawnmower is based on the price, as reported by Abdul Aziz et al. (2020) [101]. This leads to the use of hollow steel as the body frame and handle and aluminum alloy for the decks of the lawnmower prototype.

As a significant factor, it is good to include cost accounting when developing a smart lawnmower. This will provide the researcher with an overview of their product price in comparison to products in the market. Additionally, this would be useful for the researchers in planning a start-up company to manufacture and sell the lawnmowers. Kang et al. (2021) [7] reported that the cost of producing a single prototype of a multi-functional smart lawnmower is around USD 130. By considering the variable cost, fixed cost, break-even analysis, and profit margin, the prototype can be priced at approximately

USD 230, which is about 10 times cheaper than other competitors with similar specifications in the market.

The cost analysis of a lawnmower was also conducted by Mandal and Borah (2024) [26]. The analysis covers the expenses related to individual components, fabrication, and miscellaneous items required for the construction and operation of the lawnmower. The summary of the cost for a solar lawnmower over 5 years of usage was calculated to be approximately USD 165, comprising the initial product cost and low maintenance cost. On the other hand, the summary of the cost for a gasoline grass cutter was calculated to be approximately USD 410, comprising the initial product cost, fuel cost, and maintenance cost. This comparative cost analysis highlights the economic advantage of a smart lawnmower. Incorporating such cost analysis in the early design and development phase can significantly improve the product marketability and market competitiveness.

4. Recommendations for Future Research

4.1. Short-Term Directions

The integration of diverse factors, including the evaluation of lawnmower performance across multiple studies, can establish an important criterion list that paves the way for the future development and advancement of smart lawnmowers. Evaluating numerous indicators such as the operating time, FCe, and field efficiency (%) would provide an idea of how smart lawnmowers of the future can be developed to adapt to their environment.

One of the studies could include conducting an experimental design approach in order to facilitate the hypothesis testing of the factors and sub-factors in the research framework. With reference to the experimental paradigm, researchers could use the analysis of variance (ANOVA) with a p-value of 0.05 to establish statistical significance for several parameter combinations. The ANOVA would be used to check the effect of one or more variables on the performance parameter by comparing the means of different samples from the data collected through various experiments [102].

The dependent variables that could be analyzed by studies are the forward speed, field capacity, and field efficiency of the smart lawnmower. These dependent variables would rely on several independent variables. These independent variables could be categorized as the types of grass, the version of the prototype, and the levels of grassland. Each independent variable category can be divided into sub-categories. Cow grass and carpet grass could serve as sub-categories for the types of grass. The version of the prototype could include the use of an old or existing lawnmower and a new or experimental lawnmower. Finally, the levels of grassland could consist of unlevelled grass and levelled grass.

Although this framework still requires further tests, it involves creating a new experimental design approach by assessing the literature review findings on the operating time, Effective Field Capacity (FCe), and field efficiency (%) of a smart lawnmower. The developed framework enhances our knowledge on how these dependent variables would be affected by independent variables such as the types of grass, the version of the prototype, and the levels of grassland.

4.2. Long-Term Directions

Firstly, future research can focus on developing more energy-efficient smart lawnmowers that can operate for a longer duration on a single charge. Smart lawnmowers are mostly powered by batteries or electricity, which can be costly and inefficient. One approach could be to develop more solar or other renewable energies to power these machines.

Following this, future research can also focus on developing more advanced sensor technology that can help these smart lawnmowers navigate more efficiently and accurately. Smart lawnmowers rely heavily on sensor technology to navigate around obstacles and

avoid collisions. This could include the LIDAR (Light Detection and Ranging) or other advanced sensors to help smart lawnmowers map out the environment more effectively.

While smart lawnmowers are already highly autonomous, future research could focus on developing even more advanced autonomous capabilities. For example, researchers could explore the use of machine learning algorithms to help these devices learn and adapt to their environment over time, making them even more efficient and effective.

Although smart lawnmowers are generally safe to use, there is always the risk of accidents occurring. Future research can focus on developing more advanced safety features that can help prevent accidents and injuries. For example, researchers could explore the use of advanced collision detection and avoidance systems to help smart lawnmowers avoid obstacles and other hazards.

In addition, although these smart lawnmowers are designed to be user-friendly, there is always room for improvement. Future research can focus on developing more intuitive and user-friendly interfaces that make it easier for users to operate these devices. This could include the use of voice commands, touchscreens, or other advanced interfaces.

Finally, future research can focus on the environmental impact of smart lawnmowers. These devices can be highly effective at maintaining lawns and gardens. However, they can also be environmentally damaging if not used responsibly. Researchers could explore the use of more environmentally friendly materials and manufacturing processes, as well as developing more sustainable ways to dispose of smart lawnmowers at the end of their life cycle. Additionally, researchers could explore the use of smart lawnmowers as a tool for promoting biodiversity, such as by leaving certain areas of the lawn uncut to promote the growth of native plants and wildlife.

5. Conclusions

All in all, this performance review paper answers RQ1, which asks "What are the key performance indicators considering the use of smart lawnmowers?" There are a few potentially important performance considerations such as the speed, operating time, Effective Field Capacity (FCe), field efficiency (%), grass type, initial grass height, moisture (density), and labor involvement. This performance review paper also satisfies RQ2, which asks "What are the theoretical and practical implications of developing smart lawnmowers in performance such as navigation and obstacle avoidance, battery life, energy efficiency, operational efficiency, and human–machine interaction?" Smart lawnmower development and experimentation can lead to the development of more sophisticated machine learning algorithms, sensors, and communication protocols to navigate the smart lawnmower and mow the lawn autonomously. These experiments could also pave the way for the advancement of swarm robotics, which involves multiple robots working together to complete the task efficiently.

While smart lawnmowers, particularly solar-based models, offer advantages in environmental sustainability and energy efficiency, and our finding highlights opportunities to further improve these aspects through targeted performance development. Additionally, the issues discussed in several recent smart lawnmower performances reveal clear gaps that can guide both short- and long-term research, paving the way for smarter and more eco-friendly lawnmowers. Nevertheless, based on the reviewed experimental studies, smart lawnmowers have shown effectiveness in efficiently navigating and mowing lawns, possessing adequate battery capacity, enhancing the quality of lawn maintenance, successfully maneuvering around obstacles, being environmentally friendly, and demonstrating energy efficiency. These findings suggest that smart lawnmowers have the potential to be valuable tools for users seeking to save time and reduce the expenses associated with lawnmowing.

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Abbreviations

The following abbreviations are used in this manuscript:

HMI	Human–machine interaction
FCe	Effective Field Capacity
CAGR	Compound Annual Growth Rate
GPS	Global Positioning System
LiDAR	Light Detection and Ranging
SLAM	Simultaneous Localization and Mapping
ROS	Robot Operating System
TIS	Total Intelligent System
IoT	Internet of Things
CPP	Coverage Path Planning
TRIZ	Theory of Inventive Problem Solving
RLM	Robotic lawnmower

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