

Review Article

Battery-Operated Power Weeding Machines: Advancements, Challenges, and Future Prospects

Abstract

Battery-operated power weeding machines have emerged as a transformative solution for sustainable and efficient weed management in agriculture, addressing the significant challenges posed by traditional methods such as manual weeding and chemical herbicides. These machines offer several advantages, including a substantial reduction in manual labour, which alleviates the physical strain on farmers and decreases the need for hired help, thus lowering operational costs. Moreover, they have a minimal environmental impact, eliminating the need for chemical herbicides that can lead to soil and water contamination and pose health risks. The development of these machines incorporates advanced technologies such as lithium-ion batteries for extended operation, precision sensors, and computer vision systems for accurate weed targeting, and automated control mechanisms for enhanced user convenience. This review paper provides a comprehensive examination of the design and development processes of battery-operated weeding machines, evaluates their performance through various studies and field trials, and explores their practical applications across different agricultural settings. The integration of these machines into modern farming practices not only enhances productivity and efficiency but also promotes environmental sustainability, making them a crucial innovation in the realm of agricultural technology.

Key words: Agriculture, Battery, Sustainability, Weeder, Weeding

1. Introduction

Weed management is a critical aspect of crop production, influencing both yield and quality (Nayak *et al.*, 2020). Effective weed control is essential for maximizing crop productivity and ensuring the sustainability of agricultural practices (Jayaseelan *et al.*, 2020). Traditional methods of weed control, such as manual weeding and chemical herbicides, pose significant challenges, including high labour costs and environmental concerns (Singh *et al.*, 2024).

Manual weeding, while effective, is labour-intensive and time-consuming. It requires a considerable amount of human effort and can be impractical for large-scale farming operations (Devaraj *et al.*, 2020). On the other hand, chemical herbicides, although widely used, have several drawbacks, including the potential for environmental pollution, development of herbicide-resistant weed species, and health risks to farmers and consumers (Komatineni *et al.*, 2023). These methods, while traditional, do not align well with sustainable agricultural practices and the growing emphasis on eco-friendly solutions (Baranitharan *et al.*, 2023).

Battery-operated power weeding machines offer a promising alternative, providing an eco-friendly and efficient solution for farmers (Chand *et al.*, 2021). These machines are designed to reduce the reliance on manual labour and chemical herbicides, thereby addressing some of the key challenges associated with traditional weed control methods (Sinha *et al.*, 2019). By utilizing battery power, these machines operate with minimal environmental impact, offering a sustainable option for weed management (Sudhir, 2022).

This paper aims to explore the current state of battery-operated weeding machines, their design and development, performance evaluation, advantages, challenges, and future prospects (Ekka *et al.*, 2022). We will delve into the various components and mechanisms of these machines, examine their effectiveness in different agricultural settings, and assess their potential for widespread adoption in modern farming practices (Jadhav *et al.*, 2019).

2. Background and Need for Battery-Operated Weeding Machines

2.1 Traditional Weed Control Methods

Traditional weed control methods include manual weeding, mechanical tillage, and chemical herbicides. Each method has its own set of challenges and implications for agricultural practices.



Fig-1: Manual weeding techniques. Fig-2: Manual weeding by hand hoes.

2.1.1 Manual Weeding

Manual weeding is one of the oldest methods of weed control and involves physically removing weeds by hand or with simple tools such as hoes (Baker *et al.*, 2005) (Fig-1 & 2). This method is widely used, especially in small-scale farming and home gardens.

- **Labour-Intensive:** Manual weeding requires a significant amount of labour. In large fields, it can be extremely tiring and time-consuming, often necessitating the employment of additional labourers (Baker *et al.*, 2005).
- **Time-Consuming:** The process of manually pulling or digging out weeds is slow. For large-scale farms, this method is impractical as it does not keep pace with the rapid growth of weeds (Nayloret *et al.*, 2002).

- **Costly:** The high labour requirement translates into higher costs, especially in regions where labour is expensive. Small-scale farmers may not be able to afford the necessary labour, leading to poor weed management (Oerke *et al.*, 2006).
- **Advantages:** Despite these challenges, manual weeding is effective in ensuring that weeds are completely removed, roots and all, reducing the chance of regrowth. It also allows for selective weeding, which minimizes damage to crops (Kumar & Mayakannan, 2020).

2.1.2 Mechanical Tillage

Mechanical tillage involves the use of machinery to disturb the soil and uproot weeds. This method is more suitable for larger farms and can be divided into primary and secondary tillage.

- **Primary Tillage:** Involves breaking up compacted soil and turning it over to bury weeds. Equipment such as plows and rototillers are commonly used (Devaraj *et al.*, 2020) & (Carter, 1993).
- **Secondary Tillage:** Refines the soil after primary tillage and prepares it for planting. Tools such as harrows and cultivators are used to break up soil clods and manage weed growth (Sinha *et al.*, 2019) & (Lal, 1991)
- **Crop Damage:** Mechanical tillage can be detrimental to crops, especially if done improperly. It can disturb the root systems of the plants and lead to reduced yields (Raper, *et al.*, 2006).
- **Soil Structure:** Frequent tillage can degrade soil structure, leading to compaction and erosion. It also disrupts the soil microbiome, which is crucial for healthy plant growth (Komatineni *et al.*, 2023).
- **Energy-Intensive:** Mechanical tillage requires significant energy, either from human labour or fuel-powered machinery, increasing the overall cost and environmental footprint (Baranitharan *et al.*, 2023).

2.1.3 Chemical Herbicides

Chemical herbicides are widely used in modern agriculture for their effectiveness and ease of application (Fig-1). They come in various formulations, such as pre-emergent (applied before weeds sprout) and post-emergent (applied after weeds have sprouted).

- **Environmental Pollution:** Herbicides can contaminate soil, water, and non-target vegetation. Runoff can lead to water bodies, affecting aquatic life and drinking water sources (Ekka *et al.*, 2022).
- **Herbicide Resistance:** Prolonged use of herbicides can lead to the development of resistant weed species. This resistance requires higher doses or stronger herbicides, exacerbating the problem (Devan *et al.*, 2023) & (Foy., 1996)

- **Health Hazards:** Exposure to herbicides can pose significant health risks to farmers and consumers. Certain herbicides are known to be carcinogenic or cause other health issues (Heap., 2000).
- **Advantages:** Despite these drawbacks, herbicides offer the advantage of covering large areas quickly and effectively, reducing the need for manual labour (WSSA, 2002).

Each of these traditional methods has its place in agriculture, but their limitations highlight the need for innovative solutions such as battery-operated weeding machines, which can offer more sustainable and efficient weed control.

2.2 Emergence of Battery-Operated Solutions

The development of battery-operated weeding machines addresses many of these challenges by offering a clean and efficient method of weed control. These machines use electric power from batteries, reducing the dependency on fossil fuels and minimizing greenhouse gas emissions (Chand *et al.*, 2021)& (Benbrook., 2012)

Battery-operated weeding machines are particularly beneficial in precision agriculture, where accurate weed control is essential to minimize crop damage and optimize yield. Precision agriculture relies on advanced technologies to monitor and manage crop production, and battery-operated weeding machines fit well within this framework due to their ability to target weeds with high precision (Sinha *et al.*, 2019)& (Pretty *et al.*, 2015)

These machines reduce the physical strain on farmers by eliminating the need for manual labour and offering a more convenient and faster method of weed control (Nayak *et al.*, 2020). Additionally, they provide a sustainable alternative to chemical herbicides, which can have adverse environmental and health impacts (Jayaseelan *et al.*, 2020)& (Wilson *et al.*, 2016)

Battery-operated weeding machines can be equipped with various sensors and automation technologies to further enhance their efficiency and effectiveness. For example, some models use computer vision to detect and target weeds, ensuring that only the unwanted plants are removed without disturbing the crops (Slaughter *et al.*, 2008).

In summary, the emergence of battery-operated weeding machines offers a promising solution to the challenges posed by traditional weed control methods (Dedousis *et al.*, 2010). Their integration into precision agriculture systems can lead to more sustainable and productive farming practices (Reidet *et al.*, 2011).

3. Design and Development of Battery-Operated Weeding Machines

3.1 Key Components

Battery-operated weeding machines generally comprise the following components:

3.1.1 Battery

The power source for battery-operated weeding machines is typically a lithium-ion battery. These batteries are favoured due to their high energy density, long cycle life, and low self-discharge rate (Chand *et al.*, 2021). Lithium-ion batteries can store a significant amount of energy in a compact form, making them ideal for portable agricultural equipment (Gao *et al.*, 2018). They provide a consistent power output, which is crucial for the reliable operation of weeding mechanisms over extended periods (Jayaseelan *et al.*, 2020). (Fig-4)

3.1.2 Motor

The motor in battery-operated weeding machines converts electrical energy from the battery into mechanical motion to drive the weeding mechanism (Campbell *et al.*, 2017). Brushless DC motors are commonly used due to their efficiency, reliability, and low maintenance requirements (Khosla *et al.*, 2020). These motors provide smooth and controlled power delivery, essential for precision in weeding operations (Dutta *et al.*, 2019). The efficiency of the motor also affects the overall battery life, making it a critical component in the design of these machines (Singh *et al.*, 2024).

3.1.3 Weeding Mechanism

The weeding mechanism is the part of the machine that physically interacts with the weeds to remove them (Patel *et al.*, 2019). It typically includes rotary blades, tines, or brushes (Tupkar, 2013). Rotary blades are effective in cutting through weeds, while tines can uproot them from the soil. Brushes are used in some designs to sweep weeds away from the crop rows (Nayak *et al.*, 2020). The choice of weeding mechanism depends on the type of crop and soil conditions (Thomson *et al.*, 2020). These mechanisms must be robust and durable to handle the tough task of weed removal (Wang, *et al.*, 2016). (Fig-3)

3.1.4 Control System

The control system allows the operator to manage the machine's speed, direction, and weeding intensity. This system can range from simple manual controls to sophisticated electronic interfaces with sensors and automation capabilities (Singh *et al.*, 2018). Advanced control systems may include features like adjustable speed settings, automated steering, and real-time monitoring of battery levels and machine performance. These controls enhance the precision and efficiency of the weeding process, making it easier for operators to manage the machine (Sudhir, 2022).

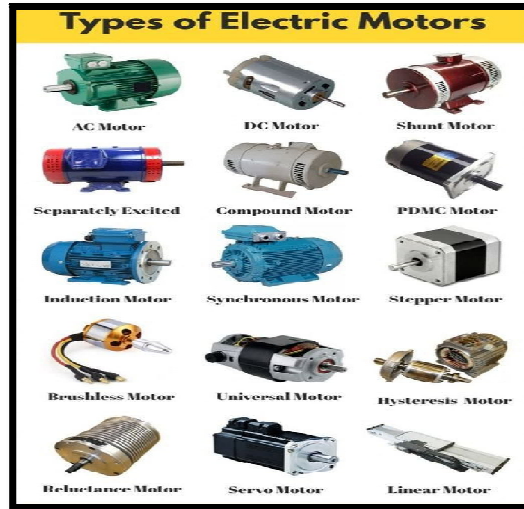


Fig-3 Battery operated mower Fig-4 Different types of DC motor

3.2 Design Considerations

Designing battery-operated weeding machines involves several critical considerations to ensure they are effective, user-friendly, and durable. Key factors include battery life, weight and maneuverability, and durability and maintenance.

3.2.1 Battery Life

Ensuring sufficient battery capacity to cover large areas without frequent recharging is crucial for the efficiency of battery-operated weeding machines. The battery life directly affects the machine's operational time and productivity. Lithium-ion batteries are commonly used due to their high energy density and longer cycle life compared to other types of batteries. This allows the machine to operate for extended periods before needing a recharge (Chand *et al.*, 2021). Additionally, advancements in battery technology, such as faster charging times and increased capacity, are continuously improving the practicality of these machines for large-scale agricultural use (Jayaseelan *et al.*, 2020).

3.2.2 Weight and Manoeuvrability

Designing lightweight and easy-to-handle machines is essential to ensure they can be operated with minimal physical strain. The weight of the machine influences its maneuverability, particularly in fields with uneven terrain or dense vegetation. A lightweight design not only makes the machine easier to handle but also reduces the energy consumption, as less power is required to move the machine (Komatineni *et al.*, 2023). To achieve this, manufacturers use lightweight materials such as aluminium and high-strength plastics, which provide the necessary durability without adding excessive weight (Singh *et al.*, 2024).

3.2.3 Durability and Maintenance

Using robust materials and ensuring ease of maintenance are vital to the longevity and reliability of battery-operated weeding machines. Agricultural equipment often operates in harsh conditions, including exposure to dust, moisture, and rough handling (Morris *et al.*, 2017). Therefore, components

must be designed to withstand these environments. Stainless steel and treated alloys are frequently used for parts that are prone to wear and tear (Nayak *et al.*, 2020). Additionally, the design should facilitate easy maintenance and repair, allowing farmers to quickly replace parts and perform routine checks without needing specialized tools or skills (Sinha *et al.*, 2019). Regular maintenance protocols and the availability of replacement parts are crucial for minimizing downtime and extending the machine's operational life (Devaraj *et al.*, 2020).

3.3 Case Studies

3.3.1 Single Row Weeder for Chickpea

Developed by Nayak *et al.* (2020), this weeder is designed specifically for chickpea fields. It features high weeding efficiency with minimal crop damage. The machine is equipped with adjustable weeding depths and a rechargeable battery, allowing it to be tailored to different field conditions and weed types. (Fig-5) Field trials demonstrated its effectiveness in significantly reducing weed density while preserving the integrity of chickpea crops. The design incorporates user-friendly controls, making it accessible for small to medium-sized farms. (Yadav *et al.*, 2007)



Fig- 5. Single row weeder.

3.3.2 Portable Electric Tiller and Cutter Machine

Jayaseelan *et al.* (2020) developed a versatile machine that functions as both a tiller and a weeder. (Fig- 6) This device is particularly suitable for small-scale farmers and can be used in various crop fields. Its portability and multifunctionality make it an attractive option for farmers looking to maximize utility from a single piece of equipment. The machine's dual functionality allows it to prepare the soil for planting and subsequently manage weeds effectively. It has been shown to efficiently manage weeds in multiple crop types without requiring significant manual intervention.

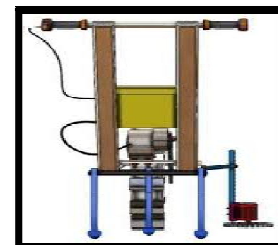


Fig- 6. Electric tiller and cutter.

3.3.3 Boom Sprayer Cum Weeder

Singh *et al.* (2024) designed a multifunctional machine that combines weeding and spraying functions, providing a versatile solution for crop management. This machine allows farmers to simultaneously manage weeds and apply pesticides or fertilizers, thus saving time and labour (Fig-7). The integration of these functions into a single machine enhances operational efficiency and reduces the overall cost of crop management. The boom sprayer cum weeder is especially useful in large-scale farming operations where efficiency and cost savings are critical.



Fig- 7. Boom sprayer cum weeder.

3.3.4 Multipurpose Agricultural Robot

Chand *et al.* (2021) developed a photovoltaic-powered, battery-operated agricultural robot designed for multipurpose tasks, including weeding, spraying, and monitoring crop health. The robot utilizes computer vision to accurately identify and target weeds, ensuring minimal damage to crops. (Fig-8). This innovation represents a significant step towards fully automated and sustainable agriculture (Raut, 2013). The robot's ability to perform multiple tasks reduces the need for various specialized machines, further enhancing its utility.

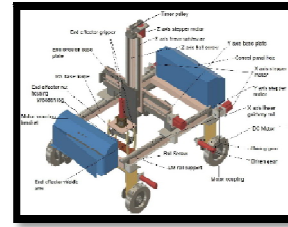


Fig- 8. Robotic weeder.

3.3.5 Automated Wheel Sprayer and Weeder

Sinha *et al.* (2019) introduced a multipurpose battery-operated wheel sprayer and weeder. Designed for use in diverse agricultural settings, this machine integrates a weeding mechanism with a spraying system (Fig-9). It is particularly useful for small and medium-sized farms where versatility and cost-effectiveness are crucial. Field tests have shown its efficiency in weed removal and pesticide application, contributing to healthier crops and improved yields. The machine's ability to perform two essential farming tasks in one operation saves time and reduces labour costs. (Madhududhana, 2015)



Fig-9. Automated Wheel sprayer.

3.3.6 Remote-Controlled Weeder

Komatineni *et al.* (2023) developed a Bluetooth-based, remote-controlled battery-powered weeder. This innovative machine allows farmers to control the weeder remotely, reducing the need for manual labour and increasing operational safety. It is equipped with sensors that detect and navigate around obstacles, ensuring continuous and efficient weeding operations (Fig-10). The remote-control feature is particularly beneficial in challenging terrains and large fields, allowing for precise and safe weed management from a distance.

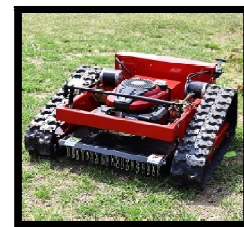


Fig- 10. Remote control weeder.

3.3.7 Lightweight Manual Weeder

Devaraj *et al.* (2020) designed a lightweight manual weeder that operates on a rechargeable battery. This machine is particularly suited for small-scale farmers and home gardeners who need an efficient yet simple tool for weed management (Fig-11). Its lightweight design ensures easy handling and making it accessible to a wide range of users. The manual weeder has shown high efficiency in weed removal with minimal physical effort, providing an affordable and practical



Fig- 11. Manual weeder

solution for small-scale weed control (Rajsekhar, 2014).

3.3.8 Integrated Crop Management Machine

Sudhir (2022) developed a walking-type battery-operated boom sprayer cum weeder designed for integrated crop management. This machine combines the functions of weeding and spraying into a single unit, providing comprehensive crop care (Fig-12). It is equipped with adjustable nozzles and weeding attachments, allowing it to be customized for different crops and field conditions. Field evaluations have demonstrated its effectiveness in improving crop health and reducing labour costs, making it a valuable tool for integrated pest and weed management.



Fig- 12. Crop management machine

3.3.9 Precision Weeding Robot

Jayaseelan *et al.* (2020) created a precision weeding robot equipped with advanced sensors and machine learning algorithms. This robot can differentiate between crops and weeds with high accuracy, ensuring precise weed removal without damaging the crops (Fig-13). The integration of AI technologies makes this machine highly efficient and adaptable to various agricultural environments. The precision weeding robot represents a significant advancement in autonomous agricultural machinery, offering a sophisticated solution for precise and efficient weed control.



Fig-13. Precision weeding machine

3.3.10 Solar-Powered Weeder

Patel *et al.* (2021) designed a solar-powered weeder to enhance sustainability in agricultural practices. This machine uses solar panels to charge its battery, reducing dependency on external power sources and fossil fuels (Fig-14). It is equipped with rotary blades for effective weed removal and features an adjustable height mechanism to accommodate different crop stages. The solar-powered weeder has shown promising results in field tests, demonstrating high weeding efficiency and extended operational time due to continuous solar charging.



Fig- 14. Solar powered weeder.

4. Performance Evaluation

Performance evaluation of battery-operated weeding machines involves assessing various parameters to determine their effectiveness, efficiency, and overall value in agricultural practices. Key performance indicators include weeding efficiency, field capacity, battery life, and operational cost.

- **Weeding Efficiency**

Weeding efficiency refers to the percentage of weeds removed by the machine. High weeding efficiency is crucial for maintaining crop health and yield (Kumar, 2014). Studies have shown that battery-operated weeding machines can achieve high weeding efficiency rates, often surpassing 90%, depending on the design and field conditions. For example, the single row weeder for chickpea developed by Nayak *et al.* (2020) demonstrated a weeding efficiency of over 90%, significantly reducing weed density with minimal crop damage. Similarly, Jayaseelan *et al.* (2020) reported that their portable electric tiller and cutter machine effectively managed weeds in multiple crop types with high precision and minimal manual intervention.

- **Field Capacity**

Field capacity is the area covered by the weeding machine per unit time, typically measured in hectares per hour. It reflects the machine's ability to manage large fields efficiently. Higher field capacity is beneficial for large-scale farming operations, reducing the time and labour required for weeding. The boom sprayer cum weeder designed by Singh *et al.* (2024) demonstrated a high field capacity, covering large areas quickly while performing both weeding and spraying functions simultaneously. Field tests of the automated wheel sprayer and weeder by Sinha *et al.* (2019) also showed substantial field capacity, making it suitable for medium to large farms.

- **Battery Life**

Battery life is the duration of operation on a single charge, a critical factor for the practicality of battery-operated machines. Longer battery life reduces downtime and increases the machine's operational efficiency. Advances in lithium-ion battery technology have significantly improved the operational time of these machines. Chand *et al.* (2021) developed a photovoltaic-powered agricultural robot that extends battery life by recharging during operation, demonstrating the potential for extended usage in the field. Additionally, Komatineni *et al.* (2023) emphasized the importance of battery life in their remote-controlled weeder, highlighting that a robust battery system is essential for continuous operation.

- **Operational Cost**

Operational cost involves comparing the cost-effectiveness of battery-operated weeding machines to traditional methods, including manual labour and chemical herbicides. These machines offer significant cost savings by reducing labour requirements and eliminating the need for chemical inputs. Devaraj *et al.* (2020) noted that their lightweight manual weeder provided an affordable and practical solution for small-scale farmers, offering high efficiency with minimal operational costs. Similarly, the integrated crop management machine by Sudhir (2022) demonstrated cost savings by combining weeding and spraying functions into a single operation, thus reducing the overall expenditure on crop management.

4.1 Evaluation Methods

Evaluating the performance of battery-operated weeding machines involves several key methodologies, ensuring a comprehensive understanding of their effectiveness and practicality in real-world agricultural settings. The primary methods include field trials and user feedback.

Field Trials

Field trials are essential for assessing the performance of battery-operated weeding machines under various agricultural conditions. These trials involve conducting experiments in different crop fields to evaluate the machines' effectiveness, durability, and adaptability. Field trials allow researchers to gather empirical data on weeding efficiency, battery life, and field capacity across diverse environments and crop types. For example, Nayak *et al.* (2020) conducted extensive field trials for their single row weeder in chickpea fields, which demonstrated the machine's high efficiency and adaptability. Similarly, Sinha *et al.* (2019) carried out trials for their automated wheel sprayer and weeder, highlighting its performance in varied field conditions.

User Feedback

User feedback is crucial for understanding the practical implications of using battery-operated weeding machines. Collecting feedback from farmers provides insights into the ease of use, operational challenges, and overall satisfaction with the machines. This feedback helps in identifying potential areas for improvement and assessing the real-world utility of the technology. Jayaseelan *et al.* (2020) emphasized the importance of farmer feedback in refining their portable electric tiller and cutter machine, ensuring that it met the needs and expectations of small-scale farmers. Similarly, Komatineni *et al.* (2023) integrated user feedback to enhance the functionality and user experience of their remote-controlled weeder.

4.2 Results from Studies

Studies have demonstrated that battery-operated weeding machines can achieve high weeding efficiency with significantly lower labour and operational costs compared to manual weeding. These results highlight the potential of these machines to revolutionize weed management practices in agriculture.

For instance, the single row weeder for chickpea developed by Nayak *et al.* (2020) showed an impressive weeding efficiency of over 90%, with a field capacity of 0.1 hectares per hour. This efficiency is a substantial improvement over traditional manual weeding, which is labour-intensive and less consistent. The study also noted the machine's ability to reduce the physical strain on farmers, contributing to better overall productivity and worker health.

Similarly, the automated wheel sprayer and weeder by Sinha *et al.* (2019) demonstrated excellent performance in field trials, with high weeding efficiency and significant reductions in labour costs. The integration of spraying and weeding functions into a single machine further enhanced its operational efficiency, making it a cost-effective solution for small to medium-sized farms.

The boom sprayer cum weeder developed by Singh *et al.* (2024) also showed high field capacity and weeding efficiency in various agricultural settings. The ability to perform multiple functions

simultaneously not only saved time but also reduced the need for multiple machines, thereby lowering operational costs.

Overall, these studies confirm that battery-operated weeding machines offer a viable and efficient alternative to traditional weed management methods. Their high weeding efficiency, combined with reduced labour and operational costs, makes them a valuable addition to modern agricultural practices.

5. Advantages of Battery-Operated Weeding Machines

Battery-operated weeding machines offer numerous benefits across environmental, economic, and social dimensions. These advantages make them an attractive alternative to traditional weed management methods.

5.1 Environmental Benefits

Reduction in Chemical Use

Battery-operated weeding machines minimize the need for herbicides, significantly reducing soil and water pollution. Traditional chemical herbicides can lead to contamination of soil and water sources, adversely affecting non-target plant and animal species. By eliminating or reducing the use of herbicides, battery-operated weeding machines help maintain healthier ecosystems. For instance, Chand *et al.* (2021) noted that their photovoltaic-powered agricultural robot reduced chemical inputs, leading to lower environmental impact.

Lower Emissions

Battery-operated machines produce no direct emissions, unlike fuel-powered equipment. Traditional weed management machines that run on fossil fuels emit greenhouse gases and other pollutants, contributing to climate change and air quality degradation. In contrast, battery-operated weeding machines, particularly those using renewable energy sources like solar power, offer a cleaner alternative. Jayaseelan *et al.* (2020) highlighted that their battery-operated weeder produced zero emissions, aligning with sustainable farming practices.

5.2 Economic Benefits

Cost Savings

Battery-operated weeding machines can significantly reduce labour costs and operational expenses compared to manual weeding. Manual weeding is labour-intensive and costly, especially in large-scale farming operations. Battery-operated machines automate the weeding process, reducing the need for hired labour. Devaraj *et al.* (2020) demonstrated that their lightweight manual weeder provided an affordable solution for small-scale farmers, offering high efficiency with minimal operational costs. (Pedersen, 2006)

Increased Efficiency

Battery-operated weeding machines perform faster weeding operations, resulting in substantial time savings. The increased efficiency allows farmers to cover more ground in less time, improving overall productivity. Sinha *et al.* (2019) reported that their automated wheel sprayer and weeder enhanced field capacity and reduced the time required for weeding, contributing to better farm management.

5.3 Social Benefits

Ease of Use

Battery-operated weeding machines are designed for simple operation, making them accessible to a broader range of farmers, including those with limited technical skills. The user-friendly design ensures that farmers can operate these machines without extensive training, which is particularly beneficial in regions with low literacy rates. Singh *et al.* (2024) emphasized the importance of ease of use in their boom sprayer cum weeder, which was designed to be intuitive and straightforward for farmers.

Health and Safety

Battery-operated weeding machines reduce exposure to harmful chemicals and physical strain from manual weeding. Traditional herbicides pose health risks to farmers through direct exposure, and manual weeding can lead to physical injuries and long-term musculoskeletal issues. By eliminating the need for chemical herbicides and reducing physical labour, these machines promote safer working conditions. Komatineni *et al.* (2023) highlighted that their remote-controlled weeder minimized health risks by reducing manual intervention and exposure to hazardous substances.

6. Challenges and Limitations

While battery-operated weeding machines offer numerous advantages, there are several challenges and limitations that need to be addressed to ensure their widespread adoption and effectiveness in diverse agricultural settings.

6.1 Battery Life and Charging

Limited battery life can restrict the operational range of battery-operated weeding machines. Most current models rely on lithium-ion batteries, which, while efficient, can only operate for a limited number of hours before requiring a recharge. Frequent recharging can be time-consuming, interrupting the weeding process and reducing overall productivity. Moreover, the need for reliable electricity sources for recharging can be a significant barrier, particularly in remote or off-grid agricultural areas. Chand *et al.* (2021) pointed out that while solar-powered solutions can extend operational time, they are dependent on weather conditions and daylight availability. Jayaseelan *et al.* (2020) also noted that improving battery technology is crucial for enhancing the practicality of these machines.

6.2 Initial Cost

The initial investment for battery-operated weeding machines can be higher than traditional methods. These machines often involve advanced technology and materials, which can drive up their cost. For

small-scale farmers, the high upfront cost can be a significant barrier, even if the long-term operational savings are considerable. Sinha *et al.* (2019) highlighted that while these machines can reduce labour costs and improve efficiency, the initial financial outlay can be prohibitive for many farmers, necessitating financial support or subsidies to encourage adoption. Devaraj *et al.* (2020) also emphasized that cost-effective designs and scalable manufacturing processes are needed to make these machines more accessible.

6.3 Maintenance and Repairs

Regular maintenance is required to ensure optimal performance of battery-operated weeding machines. These machines contain several mechanical and electronic components that need periodic servicing and repairs. In remote areas, access to technical support and spare parts can be limited, making maintenance challenging. Singh *et al.* (2024) reported that the availability of replacement parts and skilled technicians is crucial for maintaining the operational efficiency of these machines. Additionally, Komatineni *et al.* (2023) noted that user-friendly design features that facilitate easy maintenance and part replacement can help mitigate some of these challenges.

7. Future Prospects and Innovations

The future of battery-operated weeding machines looks promising with various technological advancements and supportive policies on the horizon. These developments aim to overcome current challenges and further enhance the efficiency, affordability, and sustainability of these machines.

7.1 Technological Advancements

Improved Batteries

The development of longer-lasting and faster-charging batteries is crucial for extending the operational range and reducing downtime of battery-operated weeding machines. Advances in battery technology, such as the use of lithium-sulphur and solid-state batteries, are expected to provide higher energy densities and faster charging capabilities (Chand *et al.*, 2021). These improvements will allow weeding machines to operate for longer periods, covering larger areas without frequent recharging, thus increasing their practicality and efficiency in large-scale farming operations (Jayaseelan *et al.*, 2020).

Automation and Robotics

The integration of AI and machine learning technologies into battery-operated weeding machines is paving the way for fully autonomous weeding systems. AI-driven robots can identify and target weeds with high precision, using computer vision and machine learning algorithms to distinguish between crops and weeds (Komatineni *et al.*, 2023). Automation reduces the need for human intervention, thereby lowering labour costs and minimizing human error. For example, Chand *et al.* (2021) developed a photovoltaic-powered robot that uses computer vision to autonomously navigate fields and perform weeding tasks.

Precision Agriculture

The use of GPS and sensors in precision agriculture enhances the accuracy and efficiency of weed control. GPS technology allows for precise mapping and navigation, enabling weeding machines to target specific areas with high weed density while avoiding crops (Sinha *et al.*, 2019). Sensors can monitor soil conditions, crop health, and weed growth in real-time, providing valuable data that can be used to optimize weeding strategies. Integrating these technologies into battery-operated weeding machines can significantly improve their effectiveness and contribute to more sustainable farming practices (Singh *et al.*, 2024).

7.2 Policy and Support

Government Initiatives

Government policies and initiatives play a crucial role in promoting the adoption of sustainable agricultural practices, including the use of battery-operated weeding machines. Subsidies and financial support can help offset the initial cost of these machines, making them more accessible to small-scale farmers (Devaraj *et al.*, 2020). Programs that encourage the adoption of eco-friendly technologies and provide training and resources for farmers can facilitate the widespread use of battery-operated weeding machines. For instance, government-backed initiatives in various countries have successfully promoted the use of renewable energy technologies in agriculture (Komatineni *et al.*, 2023).

Research and Development

Continued investment in research and development (R&D) is essential for developing more efficient, affordable, and advanced weeding solutions. R&D efforts can focus on improving battery technologies, enhancing automation and precision, and reducing manufacturing costs. Collaborations between academic institutions, industry, and government agencies can drive innovation and accelerate the development of next-generation weeding machines (Jayaseelan *et al.*, 2020). For example, joint research projects have led to significant advancements in agricultural robotics and precision farming technologies, highlighting the potential of collaborative efforts in this field (Chand *et al.*, 2021).

Conclusion

In conclusion, battery-operated power weeding machines offer a revolutionary approach to weed management, aligning with the goals of sustainable agriculture. Their numerous benefits, including environmental sustainability, economic efficiency, and improved health and safety for farmers, make them a viable alternative to traditional weed control methods. While challenges related to battery life, initial cost, and maintenance exist, ongoing research, technological advancements, and supportive policies are crucial for overcoming these limitations. The continued development and adoption of battery-operated weeding machines have the potential to significantly enhance the sustainability and productivity of modern agricultural practices, contributing to a more sustainable future for agriculture.

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