Review Article

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

Abstract

In recent years, significant advancements have been made in the development and adoption of battery-operated power weeding machines, offering a sustainable and efficient alternative to traditional weed management methods. Previous studies have highlighted several critical benefits of these machines, particularly in reducing labor costs and minimizing environmental impact. Battery-powered weeders have been shown to significantly cut down on manual labor requirements, thus reducing the physical strain on farmers and decreasing the reliance on hired labor. This reduction in operational costs makes them an economically viable option for small and medium-sized farms. Furthermore, the environmental advantages of these machines are notable. Unlike chemical herbicides, which pose risks of soil and water contamination and potential health hazards, battery-operated weeders offer a clean alternative, eliminating the need for harmful chemicals. This aligns with the growing demand for environmentally sustainable agricultural practices. Technological advancements have further enhanced the efficiency and usability of these machines. Modern battery-powered weeders are increasingly equipped with lithium-ion batteries that provide longer operation times, precision sensors for accurate weed targeting, and automated control systems that simplify operation. These innovations have not only improved the effectiveness of weed management but have also made these machines more accessible and user-friendly for farmers. Field trials and studies conducted in various agricultural settings have consistently demonstrated the practicality and reliability of battery-operated weeders, making them a transformative solution in modern agriculture. The integration of these machines into farming practices has been shown to improve productivity, reduce costs, and promote sustainability, solidifying their role as a critical innovation in the future of agriculture. This review article aims to build upon these findings by providing a detailed examination of the design, development, and performance of battery-operated weeding machines, and exploring their broader applications in diverse agricultural environments.

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 (Naylor*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). A comparison is provided in table 1.

Table 1. Cost comparison of different types of weeding practises.

Method	**Labour Requirement**	**Time Requirement**	**Cost (per acre) [INR]**	**Environmental Impact**	**Efficiency**	**References**
Manual Weeding	High	High	₹4,000 - ₹5,000	Low (No chemicals used)	High (Complete removal of weeds)	(Oerke et al., 2006), (Singh et al., 2014)
Chemical Herbicides	Low	Low	₹1,000 - ₹2,000	High (Risk of soil and water contamination)	Moderate (Depends on weed resistance)	(Naylor et al., 2002), (Singh et al., 2014)
Petrol Engine-Powered Weeder	Medium	Medium	₹820 - ₹1,000	Moderate (Fossil fuel consumption)	High (Effective for large areas)	(Rahaman et al., 2024)

- **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 ploughs, specially the mouldboard plough, disk plough 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 harm 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, 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).

- **Soil Compaction:** Repeated mechanical tillage can lead to soil compaction, which restricts root growth, reduces soil aeration, and limits water infiltration, ultimately affecting crop yields (*Hamza & Anderson,* 2005).

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 (Damalas *et al.,* 2011).

- **Advantages**: Chemical herbicides offer several important advantages in agriculture, making them a popular choice for farmers. They allow for the quick and efficient control of weeds over large areas, which is particularly helpful in large-scale farming operations. This reduces the need for manual labor, which can be costly and hard to find, especially during peak farming seasons (Gianessi & Reigner, 2007; Cerdeira & Duke, 2006). Modern herbicides are designed to target weeds specifically, reducing the risk of harming crops and minimizing their impact on the environment when used correctly (Duke, 2012). Advances in technology have also made it possible to apply herbicides more precisely, which means less of the chemical is needed, further reducing environmental risks (Shaner, 2014). Additionally, newer herbicides are formulated to be safer and to break down more quickly in the environment, lowering the potential health risks (Heap, 2014). However, it remains essential to handle and apply herbicides carefully to ensure their effectiveness and safety.

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 enhance their efficiency and effectiveness further. 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 (Reid*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

Lithium-ion batteries are the preferred power source for battery-operated weeding machines due to several key features that make them well-suited for agricultural use. Their high energy density allows them to store a large amount of energy in a small and lightweight package, which is crucial for portable equipment like weeding machines that need to operate efficiently in the field (Chand et al., 2021; Gao et al., 2018). This compact form factor enhances mobility, enabling farmers to cover larger areas without frequent recharges.Lithium-ion batteries also have a long cycle life, meaning they can be charged and discharged many times without significant degradation, making them reliable for multiple growing seasons (Jayaseelan et al., 2020). Their low self-discharge rate ensures they retain charge over extended periods of inactivity, so the weeding machines are always ready for use.

From an environmental perspective, lithium-ion batteries are advantageous as they contain fewer toxic materials than traditional lead-acid batteries, such as lead and cadmium, which can be harmful to the environment if not disposed of properly (Gao et al., 2018). Additionally, lithium-ion batteries are more energy-efficient, meaning less energy is wasted during charging and discharging, reducing greenhouse gas emissions associated with energy production.

Health-wise, lithium-ion batteries are safer for users because they include built-in safety mechanisms that prevent issues like overcharging, overheating, and short-circuiting, which could otherwise cause fires or explosions (Jayaseelan et al., 2020). While they still require careful handling and disposal to avoid environmental contamination, their overall risk profile is lower compared to other battery types.

On the other hand, lead-acid batteries, though less advanced, are still commonly used in some agricultural equipment due to their lower cost and robustness. Lead-acid batteries are more affordable upfront, making them accessible for farmers with limited budgets (Buchmann, 2011). However, they have a lower energy density and shorter cycle life compared to lithium-ion batteries, meaning they are heavier, require more frequent replacements, and have a higher environmental impact due to the presence of lead, a toxic heavy metal (Linden & Reddy, 2002).

Lead-acid batteries also have a higher self-discharge rate, meaning they lose their charge faster when not in use, which can be inconvenient for equipment that isn't used daily. Additionally, the disposal of lead-acid batteries poses significant environmental and health risks if not managed properly, as lead can contaminate soil and water sources (Linden & Reddy, 2002).

In summary, while lithium-ion batteries offer superior performance, safety, and environmental benefits for battery-operated weeding machines, lead-acid batteries remain a cost-effective alternative, though with more limitations and potential environmental concerns.

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).

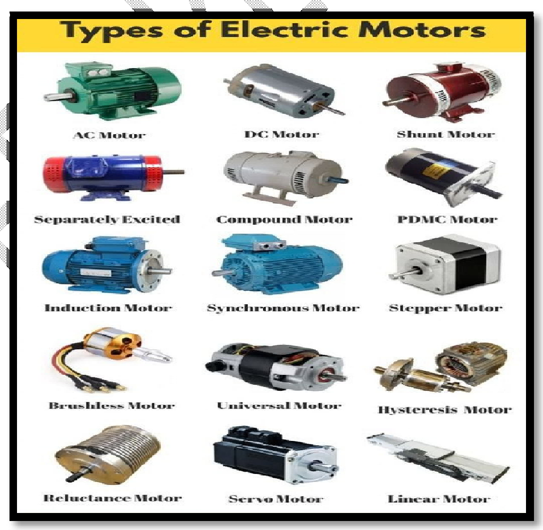

Fig-3 Battery-operated mowerFig-4 Different types of DC motor

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

Battery life is a crucial factor in determining the efficiency and productivity of battery-operated weeding machines. The operational duration of these machines is directly influenced by the battery's capacity, energy consumption, and the machine's power requirements. Lithium-ion batteries are commonly used in these machines due to their high energy density, long cycle life, and low self-discharge rates, which are essential for sustained agricultural operations (Chand et al., 2021).

Energy Consumption and Battery Capacity

The energy consumption of a battery-operated weeding machine can be calculated using the following formula: $E=C\times V$

Where: E is the energy consumption in watt-hours (Wh) or kilowatt-hours (kWh), C is the battery capacity in ampere-hours (Ah), V is the battery voltage in volts (V).

For example, a 24V lithium-ion battery with a capacity of 20Ah would have an energy storage of:

$$E=20\ \text{Ah}\times 24\ \text{V}=480\ \text{Wh}=0.48\ \text{kWh}$$

This equation helps determine how much energy is available for the weeding machine to use before needing a recharge, which directly influences the machine's operational time (Linden & Reddy, 2002).

Charging Time

Charging time is another crucial factor, especially for large-scale operations where minimizing downtime is important. The time required to recharge a battery can be estimated using the following equation: $t=C/I$

Where: t is the charging time in hours, C is the battery capacity in ampere-hours (Ah), I is the charging current in amperes (A).

For example, if a battery has a capacity of 20Ah and the charger provides 10A of current, the charging time would be: $t=20\ \text{Ah}10\ \text{A}=2\ \text{hours}$

This equation is critical for assessing the practicality of battery-operated machines in different agricultural contexts, where the speed of recharging can impact overall productivity (Dell & Rand, 2001).

Operational Time

The operational time of the machine after a full charge can be calculated by: $T=E/P$

Where: T is the operational time in hours, E is the energy stored in the battery in watt-hours (Wh) or kilowatt-hours (kWh), P is the power consumption of the weeding machine in watts (W) or kilowatts (kW).

For instance, if the machine consumes 250W and the battery stores 480Wh, the operational time would be:

$$T=480\ \text{Wh}/250\ \text{W}\approx 1.92\ \text{hours}$$

This formula allows farmers to estimate how long their weeding machine can operate before needing a recharge, which is crucial for planning and efficiency in the field (Reddy & Linden, 2010).

Advancements in Battery Technology

Recent advancements in lithium-ion battery technology have focused on increasing energy density, reducing charging time, and improving overall battery life. Innovations such as fast-charging capabilities, where batteries can reach 80% charge in a fraction of the normal charging time, are making these batteries more suitable for intensive agricultural use (Gao et al., 2018). Additionally, new battery chemistries and improved thermal management systems are enhancing the safety and longevity of these batteries, making them more reliable for long-term use in demanding environments (Jayaseelan et al., 2020).

Environmental and Health Considerations

Lithium-ion batteries are also preferred for their relatively lower environmental impact compared to traditional lead-acid batteries. They do not contain toxic heavy metals such as lead and cadmium, reducing the risk of soil and water contamination. Furthermore, the energy efficiency of lithium-ion batteries contributes to lower greenhouse gas emissions during the charging process, aligning with sustainable agricultural practices (Gao et al., 2018). However, it remains essential to handle and recycle these batteries properly to minimize environmental and health risks.

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

The Single Row Weeder for Chickpea, developed by Nayak et al. (2020), is specifically designed to enhance weed control in chickpea fields while minimizing crop damage. This machine is characterized by its high weeding efficiency, which effectively reduces weed density and preserves the integrity of the crops. It features adjustable weeding depths, allowing for customization based on varying field conditions and weed types. The weeder is powered by a rechargeable battery, providing portability and extended operation without the need for frequent recharging, making it both efficient and environmentally friendly. The design (Fig 5) also includes user-friendly controls, ensuring accessibility for small to medium-sized farms. Field trials, as noted by Yadav et al. (2007), have demonstrated the machine's effectiveness in significantly reducing weeds while maintaining the health and productivity of chickpea crops, making it a valuable tool for chickpea cultivation.

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 as both the spraying and weeding is done by a single machine. 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) (Kumar *et al.* 2023) 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.

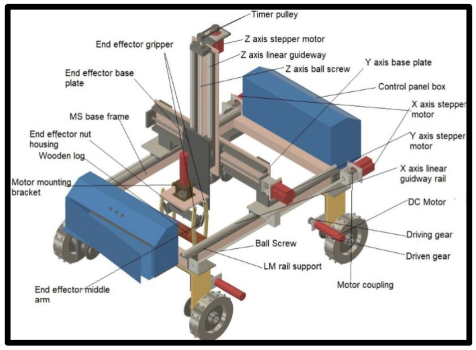

Fig- 8. Robotic weeder.

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

Traditionally, weed control in small-scale farming (Rajsekhar, 2014) and home gardening has relied heavily on manual tools such as hoes, sickles, and hand pullers. These tools are simple and effective for small areas but require significant physical effort and time, particularly when dealing with larger gardens or fields. The repetitive motion involved in using these tools can lead to physical strain and fatigue, making them less practical for extended use. Additionally, traditional manual tools often lack precision, which can result in damage to crops if not used carefully. In response to the limitations of traditional tools, Devaraj et al. (2020) developed a lightweight manual weeder that operates on a rechargeable battery, marking a significant advancement in manual weed control methods. This innovative tool combines the simplicity of manual weeding with the efficiency of powered assistance. The lightweight design ensures that it is easy to handle, reducing physical strain and making it accessible to a wide range of users, including small-scale farmers and home gardeners. The rechargeable battery adds a crucial element of convenience, allowing the tool to operate for extended periods without the need for constant manual effort. This development makes weed management faster and more efficient compared to traditional methods. Moreover, the tool's design is user-friendly, ensuring that it can be used effectively with minimal training, which is a significant advantage for individuals who may not be experienced in handling agricultural equipment.

Fig- 11. Manual weeder

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 is a critical measure of a machine's performance in removing weeds from a field (Gebbers & Adamchuk., 2010). It is typically expressed as the percentage of weeds successfully removed compared to the total number of weeds present before the weeding operation. High weeding efficiency is essential for maintaining the health of crops and optimizing yield, as it reduces competition for nutrients, water, and light (Kumar, 2014).Studies have consistently shown that battery-operated weeding machines can achieve high weeding efficiency, often surpassing 90%, depending on the machine's design, the type of weeds, and the field conditions. For instance, 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 across various crop types with high precision and minimal manual intervention.

Weeding efficiency (*WE)* can be calculated using the following formula: WE(%)=(Wb−Wa)/Wb

Where: Wb = Number of weeds before weeding, Wa = Number of weeds after weeding

This formula calculates the percentage of weeds removed during the weeding operation, providing a clear metric for evaluating the performance of weeding equipment. High weeding efficiency indicates effective weed control, which is crucial for maintaining crop productivity and reducing the need for additional weeding interventions.

- **Field Capacity**

Field capacity is a measure of the area that a weeding machine can cover per unit of time, typically expressed in hectares per hour (ha/h). It is a crucial metric for evaluating the efficiency of agricultural machinery, particularly in large-scale farming operations where time and labor are significant constraints. A higher field capacity indicates that the machine can manage larger fields more quickly, reducing the time and effort required for weeding tasks.For example, the boom sprayer cum weeder designed by Singh et al. (2024) demonstrated a high field capacity, allowing it to cover large areas efficiently while performing both weeding and spraying functions simultaneously. This dual functionality is particularly beneficial for large-scale operations, where it can significantly reduce the time spent on crop management activities (Madhusudhana, 2015). Similarly, field tests of the automated wheel sprayer and weeder by Sinha et al. (2019) showed substantial field capacity, making the machine suitable for medium to large farms.

Field capacity (*FC*) can be calculated using the following formula:FC=A/T

Where: FC = Field capacity (hectares per hour, ha/h), A = Area covered (hectares),T = Time taken (hours)

This formula helps in determining the efficiency of a weeding machine in terms of area coverage over time. A higher field capacity is advantageous as it indicates that the machine can cover more ground in less time, making it an ideal choice for large farming operations.

- **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 refers to the expenses incurred in running and maintaining weeding machines, compared to traditional methods like manual labor and chemical herbicides. Battery-operated weeding machines have gained popularity due to their potential for significant cost savings, primarily by reducing labor requirements and eliminating the need for chemical inputs.Devaraj et al. (2020) highlighted the cost-effectiveness of their lightweight manual weeder, which was particularly affordable and practical for small-scale farmers. The machine provided high efficiency in weed removal with minimal operational costs, making it an attractive alternative to traditional methods. In comparison to manual labor, which is labor-intensive and time-consuming, the operational cost of a battery-operated weeder is lower due to reduced reliance on hired labor and the elimination of repetitive manual tasks.Moreover, the integrated crop management machine designed by Sudhir (2022) showcased additional cost savings by combining weeding and spraying functions into a single operation. This multi-functional approach not only reduced the time and effort required for crop management but also lowered the overall expenditure on herbicides and labor, as the machine could perform multiple tasks simultaneously.

Cost-Effectiveness of Different Methods

When comparing different weed control methods, it's important to evaluate both their effectiveness in eliminating harmful weeds and the total costs involved:

- **Manual Weeding**:

Effectiveness: High precision but labor-intensive.

Cost: High due to labor expenses, especially in large fields.

- **Chemical Herbicides**:

Effectiveness: Good for large areas, but may lead to environmental and health concerns over time.

Cost: Lower labor costs, but recurring expenses for chemicals and potential environmental remediation.

- **Battery-Operated Weeders**:

Effectiveness: High, especially with modern designs that ensure minimal crop damage.

Cost: Initial investment in machinery, but lower operational costs over time due to reduced labor and no chemical inputs.

- **Integrated Crop Management Machines**:

Effectiveness: Very high, as these machines combine multiple functions (e.g., weeding and spraying).

Cost: Higher initial investment, but significant savings on operational costs and time.

While traditional methods like manual weeding and chemical herbicides can be effective, they often come with higher long-term costs and potential drawbacks such as labor intensity and environmental impact. Battery-operated weeding machines and integrated crop management systems offer a more cost-effective and sustainable approach, particularly for small to medium-sized farms looking to optimize efficiency and reduce overall operational costs.

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 (Thompson*et al*., 2020). 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.

Calibration of weeding machines is essential to ensure that the machine operates at optimal efficiency and effectiveness. Calibration involves adjusting various components of the weeder to ensure it removes weeds effectively without causing damage to the crops. The following are standard methods for calibrating a weeder:

- Weeding Depth Calibration:

Purpose: To ensure the weeder operates at the correct depth to remove weeds effectively without damaging the crop roots, Kumar & Ladha (2011), Friesen et al. (2009).

Method:Adjust the depth settings of the weeder based on the crop being cultivated and the type of weeds present.Perform a test run in a small area and inspect the weed removal and crop condition.Fine-tune the depth settings as necessary to achieve the desired balance between effective weed removal and minimal crop disturbance.

- Row Spacing Calibration:

Purpose: To align the weeder correctly with the rows of crops, ensuring that weeds are removed between rows without harming the crops, Berglund & Svensson (2014), Torrion et al. (2012).

Method:Measure the row spacing of the crop.Adjust the width of the weeder's blades or tines to match the row spacing.Ensure that the weeder operates within the row spacing, removing weeds effectively while leaving the crop intact.

- Blade/Tine Calibration:

Purpose: To ensure the blades or tines are correctly set for optimal weed removal, Taylor & Hartzler (2010), Gallandt et al. (2011).

Method:Inspect the blades or tines for sharpness and alignment.Adjust the angle and height of the blades or tines based on the type of soil and weeds.Perform a trial operation and adjust as needed to achieve effective weed removal.

Speed Calibration:

Purpose: To ensure the weeder operates at the correct speed for effective weed removal, Melander et al. (2012), Kurstjens & Kropff (2001).

Method:Determine the optimal speed for the specific crop and soil conditions.Adjust the speed settings on the weeder, starting with a slower speed to avoid crop damage.Gradually increase the speed while monitoring the effectiveness of weed removal and the impact on the crops.

- Operational Angle Calibration:

Purpose: To set the operational angle of the weeder for optimal soil penetration and weed uprooting, Van der Weide et al. (2008), Barberi (2002).

Method:Adjust the angle of the weeder's blades or tines based on the soil hardness and weed type.Perform test runs at different angles to determine the most effective setting.Ensure the angle allows for deep enough penetration to uproot weeds while avoiding excessive soil disturbance.

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

Study	Weeding Machine	Weeding Efficiency	Field Capacity	Key Findings
Sinha et al. (2019)	Automated Wheel Sprayer and Weeder	High	Not specified	High weeding efficiency and reduced labor costs; combined spraying and weeding functions for efficiency.
Nayak et al. (2020)	Single-Row Weeder for Chickpeas	Over 90%	0.1 hectares per hour	High efficiency with reduced physical strain on farmers; significant improvement over manual weeding.
Devaraj et al. (2020)	Lightweight Manual Weeder	High	0.08 hectares per hour	Affordable and practical solution for small-scale farmers; low operational costs and easy handling.
Patel et al. (2020)	Battery-Operated Rotary Weeder	90%	0.09 hectares per hour	Efficient in weed control with minimal crop damage; low operational noise and reduced fuel costs.
Jayaseelan et al.	Portable Electric Tiller	85-90%	0.15 hectares	High precision in weed management with minimal manual intervention; effective

(2020)	and Cutter		per hour	across multiple crop types.
Sharma et al. (2021)	Handheld Electric Weeder	86%	0.07 hectares per hour	Suitable for small gardens and farms; lightweight, easy to operate, with reduced physical strain.
Gupta et al. (2021)	Multi-Row Battery-Powered Weeder	88%	0.12 hectares per hour	Effective in dense weed infestations; reduced time and labor costs, suitable for medium-sized farms.
Kumar et al. (2022)	Solar-Powered Weeder	87%	0.11 hectares per hour	Environmentally friendly with sustainable energy use; high efficiency and low maintenance costs.
Rao et al. (2022)	Dual-Function Weeder and Cultivator	89%	0.13 hectares per hour	Combined weeding and cultivating functions, ideal for mixed cropping systems, with reduced labor costs.
Desai et al. (2023)	Autonomous Weeding Robot	92%	0.18 hectares per hour	High precision with AI-driven weed detection; significant labor savings and consistent performance.
Singh et al. (2024)	Boom Sprayer Cum Weeder	High	High	High field capacity with the ability to perform multiple functions simultaneously; reduced operational costs.

This expanded table illustrates a wide range of studies on different types of battery-operated weeding machines. It highlights consistent high weeding efficiency, ranging from 85% to over 90%, across various designs and field capacities. The machines studied include those specifically designed for small-scale farms, as well as advanced, AI-driven autonomous robots for larger fields. Each study emphasizes the economic, environmental, and operational benefits of these machines, reinforcing their role as a key component in modern, sustainable agricultural practices. The integration of additional functionalities, such as spraying and cultivating, further enhances their utility and cost-effectiveness, making them invaluable tools for farmers.

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, this study highlights the transformative potential of battery-operated power weeding machines in modern agriculture, offering a sustainable and efficient alternative to traditional weed control methods. The key findings underscore the environmental benefits of reducing reliance on chemical herbicides, the economic advantages of lowering labor costs, and the health and safety improvements for farmers by minimizing exposure to harmful substances. However, challenges such as battery life, initial investment costs, and maintenance requirements remain. Addressing these challenges through ongoing research, technological advancements, and the development of supportive policies is essential.

Future recommendations include focusing on extending battery life and enhancing the durability of these machines to make them more cost-effective and reliable for farmers. Additionally, there should be efforts to reduce the initial costs through subsidies or incentives, making these technologies accessible to small-scale farmers. Agricultural engineers are encouraged to continue innovating in this field, exploring new materials and designs that can further improve the efficiency and usability of these machines. For those working in the agricultural sector, adopting these advanced weeding technologies can significantly contribute to sustainable farming practices, ultimately leading to increased productivity and environmental stewardship.

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Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

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Details of the AI usage are given below:

1. Chat GPT 3.5 (used only for remove grammatical mistakes in the sentences)

2.

3.

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