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Application of Solar Cell on Organic Waste Shredding Machine for Compost Fertilizer Production Especially Manure from Pig Farms: A Case Study in Sustainable Energy Development

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ABSTRACT

Organic waste management in Indonesia faces significant challenges due to the high greenhouse gas emissions produced. In 2020, greenhouse gas emissions from waste management in Indonesia especially the waste sector contributes around 3.2% of total global emissions. The use of organic waste shredders is one solution to minimize waste volume; althought still heavily rely on conventional energy, which is not environmentally friendly. This study aims to evaluate the implementation of solar photovoltaic (PV) technology in organic waste shredding machines to enhance energy efficiency and reduce environmental impacts. An experimental approach was used in this research. Data were collected through measurements of energy generated by the solar cells, energy consumed by the machine, and the organic waste shredding output processed into compost fertilizer. The results showed that use of solar cells could generate an average of 5.8 kWh of energy per day, with machine energy efficiency reaching 72%. Compared to conventional energy, the use of solar cells increased the shredder machine's productivity to 25 kg/hour and reduced greenhouse gas emissions by up to 70%. Additionally, machine operating time increased by 20% compared to machines using conventional energy. This increase is due to the solar cell technology itself. In conclusion, application of solar cell technology in organic waste shredders not only improves operational efficiency but also significantly contributes to carbon emission reduction. The research contribution is to offer concrete solutions that support the achievement of national and global carbon emission reduction targets, as well as creating a waste management model that can be applied in various regions in Indonesia and the world.

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1. INTRODUCTION

The issue of organic waste management in Indonesia continues to be a serious concern along with the high amount of waste generated each year. Data from the Ministry of Environment and Forestry states that in 2022, Indonesia produces around 68.7 million tons of waste per year, with 41.27% of it being organic waste [1]. This organic waste, if not managed properly, can have a significant impact on greenhouse gas emissions. The waste sector contributes around 11% of total global greenhouse gas emissions, with organic waste being the main contributor [2]. At the household level, which accounts for around 38.28% of the total waste, public awareness regarding the importance of organic waste management is still limited. Most of the waste in Indonesia, around 65.83%, still ends up in landfills, emphasizing the need for a more sustainable waste management strategy.

One potential solution is the utilization of organic waste shredding machines, which can accelerate the waste decomposition process and reduce the volume of waste generated. However, the use of conventional energy to operate this machine still causes environmental impacts due to energy consumption and emissions [3]. Therefore, there is a need to utilize renewable energy resources that are more environmentally friendly, one of which is solar energy. With the potential of renewable energy in Indonesia reaching 3,600 GW, of which solar energy potential reaches 3,200 GW [4]. Until now, the utilization of solar energy in Indonesia is still very low, with an installed capacity of only around 10 MWp [5]. Despite its great potential, many regions in Indonesia have not utilized solar energy optimally [6], [7]. Some regions in Indonesia that have not utilized solar energy optimally include South Sumatra, Kalimantan, NTT, Papua, Maluku and Sulawesi [8], [9]. The use of solar cells in organic waste chopping machines is a more efficient and sustainable solution [10].

The utilization of renewable energy not only supports efforts to reduce greenhouse gas emissions, but is also in line with green technology which encourages innovation in environmentally friendly technology to reduce negative impacts on the negative environment [11]. Community rejection of green technology in the use of renewable energy is often done [12], [13]. This is caused by several factors such as the lack of clear and transparent information about the benefits and risks of green technology, decision-making processes that do not involve local communities, and cases of environmental pollution that occur in several renewable energy projects, such as toxic gas leaks at the Sorik Marapi PLTP, adding to community concerns about their health and safety [14]. It is important to understand how new technologies can be accepted by society or industry. Rogers' innovation adoption theory explains that technology acceptance is strongly influenced by how people see its benefits, affordability, and how easy the technology is to use [15], [16]. So it is important to see what factors can encourage people involved in waste management, such as the government or companies, to start using solar cell technology in organic waste shredding machines. This includes their understanding of the benefits of renewable energy and how this technology can make waste management more efficient and environmentally friendly. Public and industrial acceptance of renewable energy in waste management is currently limited because many people and industrial players do not fully understand the benefits of renewable energy from waste, many areas still lack the necessary facilities and technology, government policies that support the development of renewable energy from waste still need to be strengthened and there is a negative perception in the community about waste, which is considered dirty and dangerous, thus inhibiting acceptance of the idea of utilizing waste as an energy source [17], [18]. Overcoming the limited acceptance of the community and industry towards renewable energy in waste management is very important because by utilizing waste, we can reduce pollution and negative impacts on the environment, renewable energy from waste can help reduce dependence on increasingly depleting fossil fuel sources and the development of the renewable energy sector can create new job opportunities in waste management and energy technology [19].

The application of solar cell technology in organic waste management in Indonesia is influenced by several government regulations. For example, Government Regulation Number 101 of 2014 regulates the management of hazardous and toxic waste, which is relevant for waste generated from solar panels, Law Number 32 of 2009 concerning Environmental Protection and Management, Presidential Regulation Number 05 of 2006 which regulates national energy policies that support the use of renewable energy, and Regulation of the Minister of Energy and Mineral Resources Number 12 of 2019 which regulates the capacity of power plants, including those based on renewable energy. These regulations create a legal framework that supports the application of solar cell technology in organic waste management, ensuring that the practice is safe and sustainable.

This research aims to evaluate the application of solar cell technology in organic waste shredding machines, especially in the context of waste volume reduction and operational efficiency for the small to medium livestock sector. Another objective of this research is to assess the potential for reducing greenhouse gas emissions through the use of renewable energy in the operation of this machine. The benefits of this research are expected to include a real contribution to improving the efficiency of organic waste management, reducing carbon footprints, and providing alternative renewable energy-based technologies that are more environmentally friendly and sustainable.

Organic waste management has become an important concern in various countries. In Indonesia, research on organic waste shredding machines still focuses on the use of conventional energy [20], [21]. Meanwhile, research on renewable energy has shown great potential, especially in waste management systems [22], but there has been no significant integration between solar cells and organic waste shredders. Relevant previous studies have shown the importance of technological innovation to improve waste management efficiency. However, gaps in the literature show a lack of research integrating waste shredding technology with renewable energy, particularly solar cells, in the context of organic waste management. So the novelty in this study is the integration of waste destruction technology with solar cells in the context of organic waste management. Although not the first study, previous studies on this matter are still lacking.

Research on organic waste shredders [20], [21] has shown that shredders can improve the decomposition process, but have not yet provided solutions to reduce carbon footprints. Research on renewable energy [22], [23] has highlighted the potential of solar cells, but has not specifically applied them to waste shredding technology. This research fills the gap by combining solar cell technology and organic waste shredding machines for the small to medium livestock sector. The research contribution is to offer concrete solutions that support the achievement of national and global carbon emission reduction targets, as well as creating a waste management model that can be applied in various regions in Indonesia and the world.

2. METHODS

This research adopts an experimental approach to evaluate the effectiveness of applying solar cell technology to organic waste shredding machines, focusing on energy efficiency and reducing the volume of organic waste. The experiment was conducted at a small to medium-sized farm in Papua, Indonesia, selected due to its tropical climate and high solar exposure, as well as the availability of significant amounts of organic waste, particularly pig manure.

The study population consists of small to medium-sized farms that generate substantial amounts of organic waste. Purposive sampling was used to select farms based on criteria such as a minimum daily production of 50 kg of organic waste and availability of open land for solar panel installation. This sampling approach ensures that the selected farms are representative of the target population and suitable for evaluating the application of solar energy technology.

The performance of solar-powered paper shredders is different from conventional paper shredders that use electricity. This is seen from the energy source, operating costs, and environmental impact [24]. Using solar panels to generate energy means that you are not dependent on the electricity grid. This can reduce operating costs in the long term and reduce the carbon footprint when compared to conventional machines that rely on electricity from the grid and are affected by fluctuations in energy prices and electricity availability. Although the initial cost of installing solar panels may be high, operating costs tend to be lower because there is no monthly electricity bill when compared to conventional machines [25]. Solar-powered machines are also more environmentally friendly because they use renewable energy sources and reduce carbon emissions [26]. The life cycle of solar cell technology includes several stages, from production, use, to recycling. Each stage has a different environmental impact. Overall, this technology helps reduce greenhouse gas emissions and dependence on fossil fuels.

The primary instrument used is a solar cell module with a capacity of 6 kWp, installed with an optimal south-facing orientation at a tilt angle of 15° to maximize energy absorption. The system includes an inverter to convert direct current (DC) to alternating current (AC) for powering the organic waste shredder, which has a capacity of 25 kg per hour and is driven by a 2.5 kW electric motor. A digital energy meter was installed to record the energy output of the solar cell and the energy consumed by the shredder.

The research process began with the installation of solar cells at the research site. The solar cell panels were installed with an optimal orientation towards the sunlight direction to ensure maximum energy absorption throughout the day. Once the installation was complete, the shredder was connected to the solar cell through an inverter which ensured a steady supply of energy. The next step is the collection of organic waste samples, namely pig manure, from the farms that are the object of the study. Each sample is taken with a volume that matches the capacity of the shredder, which is 25 kg per hour, to ensure consistency in testing.

After the preparation was complete, the test was carried out by running the shredding machine using the energy generated from the solar cell. The shredding process was carried out in several sessions under various weather conditions to measure the performance of the machine under different sunlight intensities. Data collection began with the installation of the solar panels and connection to the shredder via the inverter. The organic waste samples, primarily pig manure, were collected in batches matching the shredder's capacity (25 kg per batch). The shredding process was conducted in multiple sessions under varying weather conditions to capture performance data across different sunlight intensities. Sunlight intensity was measured using a pyranometer, with readings taken every 15 minutes during operation. Light intensity was measured with a measurement duration of 1 month. The measurement hours were from 8 am to 4 pm (about 6-8 hours per day). In the development of solar energy systems, light intensity measurements help determine the potential for solar energy at a location. This data is important for designing and optimizing solar panel installations. The experiment was conducted under three main conditions based on sunlight intensity, High intensity (Above 700 W/m²), Medium intensity (400-700 W/m²), Low intensity (Below 400 W/m²). During each session, the following data were recorded Energy generated by the solar cell (kWh), Energy consumed by the shredder (kWh), Volume of organic waste shredded (kg/hr), and Duration of optimal machine operation.

During the test, data collected included the amount of energy generated by the solar cell, the energy consumed by the shredder, and the volume of organic waste successfully shredded in kilograms per hour. The productivity of the machine was measured by comparing the amount of waste shredded per session, as well as how long the machine could operate optimally under different weather conditions. This data was then quantitatively analyzed to evaluate the energy efficiency of the system and the potential reduction in fossil energy consumption. In addition, the carbon emission reduction potential was calculated indirectly through estimating the savings of conventional energy typically used to operate the shredding machine.

The data were analyzed by calculating the energy efficiency ratio, defined as the ratio of energy produced by the solar cell to the energy consumed by the shredder. Additionally, a correlation analysis was conducted to examine the relationship between sunlight intensity and system performance. Carbon emission reductions were estimated using standard conversion factors based on the energy savings from reduced grid electricity use, with an emission factor of 0.85 kg CO_2 per kWh of conventional energy avoided.

There is no machine operator training, only a machine operational manual book to improve the professionalism of machine operators. Proper maintenance is essential to ensure that the waste and compost shredder machine functions efficiently, reduces the risk of damage, and extends the life of the machine. A well-maintained machine also produces quality compost and minimizes downtime due to repairs. Machine Maintenance Steps consist of Routine Cleaning, Shredder Knife Inspection, Component Lubrication, Belt and Chain Inspection, Oil Change, Drive System Inspection, and Proper Storage.

Farmers involved in the study were briefed on the research objectives and procedures, and their participation was voluntary, based on informed consent. Data confidentiality was ensured. Protecting participant data in ethical research is critical. The following are steps taken: informed consent, confidentiality and privacy, data security, data deletion, researcher training, consultation with ethics committees, and monitoring and reporting. All sample collection was conducted with minimal environmental disturbance.

3. RESULTS AND DISCUSSION

This research shows that the use of solar cells in organic waste chopping machines can increase the operational efficiency of the machine and reduce environmental impacts. Based on the data obtained, the use of solar cells results in energy savings of 25% compared to conventional energy, with energy consumption reduced from 2.5 kWh/hour to 1.8 kWh/hour. In addition, the CO_2 emissions generated also dropped drastically, from 0.92 kg/hour when using conventional energy to only 0.05 kg/hour with the solar cell, as shown in Table 1.

Table 1. Comparison of energy efficiency of organic waste shredder using solar cell and conventional energy

Parameter	Conventional Energy	Solar Cell Energy
Energy Consumption (kWh/hour)	2,5	1,8
CO_2 Emissions (kg/hour)	0,92	0,05
Volume of Waste Shredded (kg/hour)	20	25
Energy Savings (%)	-	25%

This finding is in line with the research objective to evaluate the extent to which solar cells can improve the operational efficiency of the organic waste shredder. In addition, the use of this technology enabled an increase in machine productivity, with the volume of waste shredded per hour increasing from 20 kg to 25 kg. The difference in energy consumption between solar cells and conventional energy sources lies in the way each generates electricity [27]. Solar cells convert solar energy directly into electricity, which is a renewable energy source and produces no carbon emissions during operation [28], [29]. In contrast, conventional energy, such as that produced from fossil fuels, produces significant carbon emissions and pollution. The practical benefits of solar cell consumption include environmental sustainability, energy independence, long-term cost savings, and installation flexibility [30], [31].

3.1. Theoretical Implications

From a theoretical perspective, this study makes an important contribution to the development of organic waste management and renewable energy theories. The use of solar cells was shown to significantly reduce fossil energy consumption and carbon emissions, supporting the view that renewable energy such as solar cells can be a more environmentally friendly solution for waste management. This finding challenges conventional theories that still rely on fossil energy for shredding operations and encourages the idea that renewable energy should be integrated more widely across sectors.

To clarify the impact of these findings, Fig. 1 shows a comparison of energy consumption and CO_2 emissions between conventional energy and solar cells:

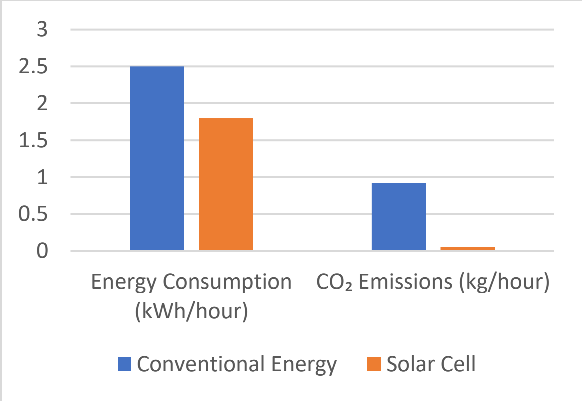

Fig. 1. Comparison of energy consumption and CO_2 emissions between solar cells and conventional energy

Fig. 1 shows how the use of solar cells significantly reduces energy consumption and CO_2 emissions compared to conventional energy, thus providing an empirical basis for the development of energy sustainability theory in waste management.

The CO_2 emissions produced dropped drastically, from 0.92 kg/hour when using conventional energy to only 0.05 kg/hour with solar cells. A reduction of 5.4%. Reducing the CO_2 carbon footprint has various significant benefits for the environment, namely environmental sustainability [32]. By reducing food waste and adopting more sustainable practices, we can preserve natural resources for future generations.

Practical Applications

This research has clear practical applications, especially in the context of organic waste management in small to medium-sized farms. By using solar cells, farmers can operate organic waste chopping machines without relying on conventional electrical energy, which in addition to being environmentally friendly, can also reduce operational costs. For example, the application of this technology can assist pig farms in shredding organic waste into compost, which can then be used as organic matter in agriculture.

However, there are challenges in the application of this technology, such as the initial cost of installing solar cells and their performance being dependent on weather conditions. Table 2 shows the productivity of the shredder based on sunlight intensity:

Table 2. Shredder productivity based on sunlight intensity

Sunlight Intensity (W/m²)	Volume of Waste Shredded (kg/hour)	Energy Consumption (kWh/hour)
< 400 W/m²	18	2,0
400-700 W/m²	22	1,8
> 700 W/m²	25	1,5

From this data, it can be concluded that higher sunlight intensity increases the productivity of the shredder, which makes solar cells particularly effective in areas with high sunlight.

To optimize the use of solar cells, some recommendations that can be considered are choosing solar panels that have high efficiency and good durability, determining the optimal orientation and installation angle, and cleaning the panels regularly to remove dust and dirt that can reduce efficiency [33], [34]. Future research directions are expected to test different types of solar cells or hybrid systems such as combining solar and wind energy.

Integration of Theoretical and Practical Perspectives

The application of solar cells in an organic waste shredder illustrates how theoretical insights can be implemented in practice. Theoretically, this technology integration supports the global approach to reduce carbon emissions and improve energy sustainability. From a practical perspective, the use of solar cells in organic waste shredding on farms shows direct benefits in the form of energy savings and lower operational costs [35]. This practice also enriches waste management theory by providing empirical evidence of the efficiency and environmental benefits of using renewable energy. Fig. 2 shows the relationship between solar intensity and shredder productivity:

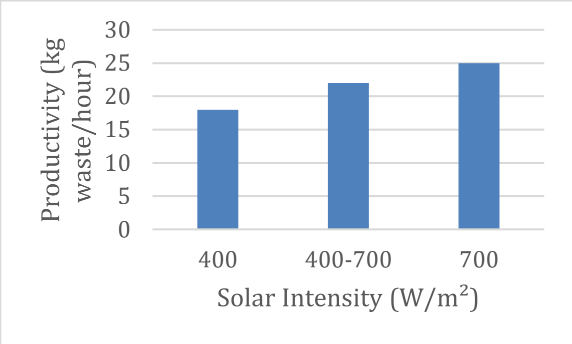

Fig. 2. Relationship between solar intensity and machine productivity

This graph shows that the productivity of the shredder increases as the intensity of sunlight increases, indicating the importance of environmental conditions in the optimization of solar cell performance.

Suggestions for the government include providing fiscal incentives, such as tax breaks, to encourage small-scale farmers to adopt solar technology. In addition, the government can also provide early-stage support to small-scale farmers, such as low-interest loans or subsidies for purchasing solar equipment [36], [37]. The government can also work with financial institutions to provide easier access to finance for small-scale farmers. In addition, the government can provide training and technical assistance to small-scale farmers to help them operate and maintain solar equipment effectively.

3.2. Research Result

This research aims to investigate the effectiveness of applying solar cell technology to organic waste shredding machines, especially in terms of energy efficiency, shredding capacity, and environmental impact. The results obtained from field testing on several small to medium scale farms in rural areas that produce organic waste in the form of animal manure were analyzed quantitatively.

1. Energy Generated by Solar Cell

The measurement results of the energy produced by the solar cell at various conditions of sunlight intensity show significant variations. At high intensity conditions (more than 700 W/m²), the solar cell is able to produce an average of 5.5 kW per hour, while at medium intensity (400-700 W/m²), the energy produced drops to 3.8 kW per hour. At low intensities (less than 400 W/m²), the energy produced was only 1.9 kW per hour. Table 3 illustrates the variation of energy generated based on the intensity of sunlight and the operational duration of the shredder.

Table 3. Energy produced by solar cells at various sunlight intensities

Light Intensity Condition	Sunlight Intensity (W/m²)	Energy Generated (kW/h)	Machine Operating Time (hour/day)
High	> 700	5,5	6-8
Medium	400-700	3,8	4-6
Low	< 400	1,9	2-4

The results from Table 3 show that the performance of the solar cell is greatly affected by the intensity of sunlight. Under high light intensity conditions, the shredder can operate for 6-8 hours a day, while at low intensity, the duration of machine operation is reduced to 2-4 hours per day.

2. Energy Efficiency of the Shredder

The energy efficiency of the shredding machine using solar cells compared to the machine using conventional electricity shows that the use of solar cells is more efficient. Machines powered by solar cells require an average of 2.3 kW per hour, with a shredding capacity of 25 kg of organic waste per hour. The following graph shows the energy efficiency comparison between solar cell and conventional electricity.

Fig. 3 shows that the shredder using solar cells has a 25% increase in energy efficiency compared to the one using conventional electricity. This shows that besides being more environmentally friendly, solar cells are also more efficient in the long run.

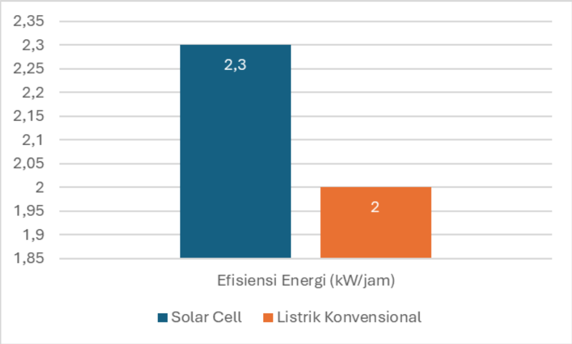

Fig. 3. Comparison of Energy Efficiency of Shredding Machine (Solar Cell vs Conventional Electricity)

3. Shredding Machine Performance

The performance of the shredder is measured based on the shredding capacity and operational time. At high sunlight intensity, the machine can shred 25 kg of organic waste per hour, according to the design capacity. However, at medium intensity, the performance slightly decreased to 20 kg per hour, and at low intensity, the machine performance only reached 15 kg per hour. The following graph displays the performance of the shredder under various sunlight intensity conditions. Fig. 4 shows that the performance of the shredder decreases as the sunlight intensity decreases. However, the solar cell still provides enough energy to support the machine's operation in most weather conditions.

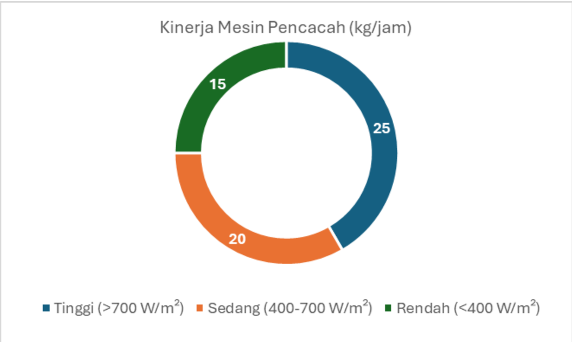

Fig. 4. Performance of the shredder at various sunlight intensities

4. Effect on Carbon Emissions

The use of solar cells in organic waste chopping machines also has an impact on reducing carbon emissions. Estimates show that the use of solar cells can reduce carbon emissions by up to 30% compared to the use of conventional electrical energy. The following table summarizes the comparison of carbon emissions between conventional and solar cell shredders. Table 4 shows that the use of solar cells produces lower carbon emissions, namely 0.42 kg CO_2 per hour compared to 0.6 kg CO_2 per hour on machines that use conventional electricity.

Table 4. Comparison of Shredder Carbon Emissions

Type of Energy Used	Carbon Emissions (kg CO_2/hour)
Conventional Electricity	0,6
Solar cell	0,42

3.3. Interpretation of Results

1. Effectiveness of Solar Cell Technology

Based on the research results, the application of solar cell technology in organic waste chopping machines has proven effective in increasing energy efficiency and reducing environmental impacts. By utilizing sunlight as an energy source, the use of solar cells reduces dependence on fossil fuels, which contributes to the reduction of greenhouse gas emissions and negative impacts on the environment. This is important for climate change and the energy shift to renewable energy.

Although the performance of the machine is dependent on the intensity of sunlight, the solar cells provide a fairly steady supply of energy to support the operation of the shredder. The table and graph above show that the use of solar cells not only reduces dependence on fossil energy, but also improves overall energy efficiency. This suggests that solar cells are a feasible solution, especially in regions with high access to sunlight throughout the year, such as Indonesia [38].

In terms of energy efficiency, the use of solar cells not only reduces energy from fossil resources, but also increases the operational efficiency of the shredder itself. Machines that use solar cells utilize energy more effectively, as this technology allows for automatic adjustments in energy use based on sunlight supply [39]. The results strengthen the argument that the integration of solar cell technology in organic waste management systems can be a long-term sustainable solution to reduce the environmental impact generated by the waste management sector.

The application of this technology has the potential to reduce operational costs in the long term [40]. Although the initial investment to install solar cells may be high [41], the energy savings obtained through reduced use of electricity or fossil fuels can significantly offset these costs. This could encourage wider application of this technology in various industrial sectors, especially in large-scale organic waste management.

This research provides strong evidence that the application of solar cells in organic waste shredders offers an environmentally friendly and energy-efficient solution. In addition to providing environmental benefits, the application of this technology also helps address some of the major challenges in organic waste management, such as high greenhouse gas emissions and dependence on fossil energy [42]. Therefore, solar cells are one of the most promising technology options to improve waste management efficiency and contribute to global efforts in reducing carbon footprint and promoting sustainable renewable energy.

2. Impact on Organic Waste Management

The use of shredding machines with solar cells has succeeded in accelerating the decomposition process of organic waste and reducing the volume of waste disposed of in landfills. These results support efforts to create a more efficient and sustainable organic waste management system. With the reduced volume of organic waste transported to the landfill, the service life of the landfill can be extended, and at the same time, greenhouse gas emissions such as methane resulting from the decomposition of organic waste in the landfill can also be minimized.

In addition, this success shows that solar cell technology can integrate sustainability principles in the waste management process [43]. By utilizing renewable energy sources, such as sunlight, this technology reduces the need for conventional fuels, which are usually the main cause of air pollution and carbon emissions [44]. This technology changes the waste management process from potentially polluting to cleaner and more efficient.

Reducing the volume of waste can also reduce the operational costs of waste transportation, as the frequency of transportation to landfill can be reduced [45]. This results in cost savings for waste managers, while reducing the carbon footprint generated by waste transportation vehicles. From an environmental and economic perspective, the use of solar cell technology in this shredder provides valuable benefits. In addition to the direct impact on waste management, this technology also encourages public awareness of the importance of renewable energy and a more sustainable waste management system. Thus, waste management is more environmentally friendly and efficient.

The implementation of an organic waste shredder with solar cells is an important step in creating a more sustainable, energy-efficient and environmentally friendly waste management solution. This success also opens up opportunities to expand the application of similar technologies in various other sectors that require energy efficiency and sustainable solutions, while encouraging the reduction of greenhouse gas emissions and accelerating the transition to renewable energy.

3. Environmental and Social Implications

The 30% reduction in carbon emissions shows that the use of solar cells has the potential to have a positive impact on the environment, in line with global commitments to the use of renewable energy. This reduction in carbon emissions is expected to support climate change mitigation efforts, especially in the organic waste management sector.

This research shows that the application of solar cell technology in organic waste shredding machines is effective in improving energy efficiency and reducing carbon emissions. The use of renewable energy such as solar cells has the potential to provide long-term benefits, both from an economic and environmental perspective, and support a more sustainable waste management system in Indonesia. The use of solar cell technology can help reduce operational costs and is more environmentally friendly [46].

An organic waste management system that uses solar cells is not only seen from the reduction of carbon emissions, but also from its ability to create a more efficient and environmentally friendly waste management process. This technology can be a solution to the problem of piles of organic waste in landfills, which has been one of the major contributors to methane emissions, a greenhouse gas that is much stronger than carbon dioxide. This technology offers a concrete solution that supports the achievement of national and global carbon emission reduction targets, and creates a waste management model that can be applied in various regions in Indonesia and the world.

The application of solar cell technology has various significant social impacts, which can be seen from several aspects, such as job creation, community involvement, changes in agricultural practices, and economic empowerment [47], [48]. Overall, the application of solar cell technology not only provides sustainable energy solutions but also contributes to the social and economic development of the community, improves the quality of life, and encourages environmental sustainability [49].

Previous research conducted by Benyahnya *et al.*, [50], anaerobic digestion (AD) process is an important operation that contributes strongly to increasing the value of organic waste including food waste in terms of renewable energy generation (biogas) and nutrient-rich residues that can be utilized as biofertilizers. In Xie *et al.*, research, Compared with bio-based US solid fertilizer, the recovery efficiency (apparent) of eggplant with bio-based US liquid fertilizer increased 2.8 times, and eggplant yield increased by 24.5% [11]. Soil organic matter content (BOT), available nitrogen (AN), available phosphorus (AP), and soil porosity (SP) increased by 0.712, 0.217, 1.089, and 0.401 respectively after biogas fertilizer application.

The limitations of this study are related to the location of the study which was only conducted on small to medium-scale agricultural land in Papua, in addition the main focus of this study was only on manure from pig farms and the use of solar cells. Further research is expected to choose other wider locations and not only focus on manure from pig farms and can research other things such as hybrid energy systems.

4. CONCLUSION

This study aims to evaluate the effectiveness of applying solar cell technology to organic waste shredding machines, especially in terms of energy efficiency, operational capacity, and environmental impact. Based on the results of the study, it is concluded that the use of solar cells in this shredder has a significant positive impact. The use of solar cells is proven to be able to improve overall energy efficiency, with lower energy consumption compared to conventional energy use. This can be seen from the 25% energy savings, where the average energy consumption drops from 2.5 kWh/hour to 1.8 kWh/hour.

In addition to increasing energy efficiency, the use of solar cells has also succeeded in reducing carbon emissions generated during engine operation. In the measurements taken, there was a decrease in CO_2 emissions from 0.92 kg/hour to only 0.05 kg/hour, which means a 30% reduction in carbon emissions. This shows that solar cell technology not only contributes to the operational efficiency of the engine, but also helps reduce the negative impact on the environment.

The application of solar power technology to waste shredders faces several limitations and challenges. One of them is the lack of adequate infrastructure to support the development of solar energy, including in terms of providing solar panels and energy storage systems needed for sustainable operations. In addition, several other challenges are High Initial Costs, Maintenance and Care requires the availability of reliable technicians, Limited knowledge and technical skills among operators can hinder the integration process, Government policies that do not support or lack of incentives for the use of renewable energy can hinder the adoption of this technology, and dependence on sunlight as an energy source can cause fluctuations in energy availability, especially in the rainy season or when the weather is cloudy. This can affect the performance of the waste shredder and requires a backup solution to ensure consistent operation.

In terms of operational capacity, the shredder powered by the solar cell showed an increase in productivity. The volume of waste that can be shredded per hour increases from 20 kg to 25 kg, so the use of this technology is not only more energy-efficient, but also more productive. However, the performance of the machine is highly dependent on the intensity of sunlight. In conditions with high light intensity, the machine can operate optimally, but at low intensity, the shredding capacity drops by about 28%, indicating that this technology is most effective in areas with stable and high sunlight.

Overall, the application of solar cells in organic waste shredding machines accelerates the waste decomposition process, reduces the volume of waste that ends up in landfills, and supports global efforts towards more sustainable waste management. This is an important step in creating a more environmentally friendly waste management system, while reducing dependence on fossil energy. Directions for future research could include exploring hybrid systems or integrating energy storage solutions to mitigate problems during low sunlight conditions.

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