Review

Solar-Powered Plant Protection Equipment: Perspective and Prospects

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Abstract: The major challenges in sustainable and profitable agriculture are developing high-yielding crop varieties and reducing crop losses. Presently, there are significant crop losses due to weed/bird/insect/animal attacks. Among the various renewable energy sources, solar energy is utilized for different agricultural operations, especially in plant protection applications. Solar photovoltaic (PV) devices present a positive approach to sustainable crop production by reducing crop loss in various ways. This might result in the extensive use of PV devices in the near future. PV-based plant protection equipment/devices are primarily utilized in protecting crops from birds, weeds, or insects. Solar-powered plant protection equipment such as light traps, bird scarers, sprayers, weeders, and fencing are gaining interest due to their lower operational costs, simple design, no fuel requirements, and zero carbon emissions. Most of these PV devices require 12 V rechargeable batteries with different currents to meet the load, which varies from 2 to 1500 W. This paper briefly discusses the applications of solar-powered plant protection devices in sustainable agriculture and their future prospects.

Keywords: plant protection; pest control; solar energy gadgets; solar insect trap; solar sprayer; solar fencing; solar weeder

1. Introduction

Agriculture production involves several operations, such as land preparation, sowing, transplanting, intercultural operation (weeding and spraying), irrigation, and harvesting of the final products such as grains, seeds, fruits, leaves, flowers, tubers, and other plant parts. To carry out these operations, farmers use different types of commercial and non-commercial energy sources. As compared to traditional farming, modern farming operations are carried out with commercial energy sources that partially replace conventional animal and human powers. Due to recent developments in farm mechanization, energy consumption in agriculture has increased with the better availability of commercial energy resources. In the current scenario, most of the tillage, plant protection, and harvesting operations are carried out with machinery attached to the tractor/power tiller. For modern agriculture, petroleum and electricity are essential in performing primary and secondary tillage and also in other mechanized operations. Electricity is the second-largest energy source used in agriculture, followed by fossil fuels, which are mainly used to operate water pumps for irrigation. Increased energy inputs and escalation of petroleum prices have significantly increased the overall cost of crop production, which has led to reduced profitability in agriculture [1]. On the other hand, overdependence on fossil
fuels and electricity in agriculture and agro-based industries/other user groups have increased greenhouse gas emissions. These factors have led to environmental pollution, global warming, and climate change.

Increasing temperature in the atmosphere due to global warming alters macro and microclimatic conditions, which also have an impact on the agroecosystem. This impact realized in terms of frequent outbreaks of existing pest pestilence and invasion of new insect pests causes reduced crop yield/production [2]. According to Van Lenteren [3], 5000 species of insects are considered harmful to crops, livestock, and human beings from among the world’s one million described insect species. Generally, a considerable economic loss occurs through loss in crop yield, which is caused by the infestation of pests such as insects, non-insect pests, birds, and weed plants. Crop losses due to weeds can vary from crop to crop based on the occurrence of weed species, locality, and farming system in the region [4,5]. Weeds compete with the main crop for nutrients, light, and water and might serve as an alternate host for insects, nematodes, and pathogens [6]. In this way, crop quality and yield can be directly reduced, and the cost of cultivation can be indirectly increased. An estimate predicted that weeds, insects, and diseases destroy about 40 percent of world crop production [7]. The global losses due to the attack of these organisms were estimated at USD 500 billion, but it can be reduced to USD 213 billion by adopting proper pest management strategies [8]. FAO’s Food Loss Index calculation depicting the first global loss estimate released in 2019 revealed that there was a 13.8 percent loss in yield due to direct (such as insect pests, diseases, post-harvest losses, etc.) and indirect (marketable loss) ways and the overall crop losses were more (0.1–18.0%) in cereals and pulses (FAO 2019).

The management of these harmful organisms is essential to maintain crop hygiene and prevent losses in crop yield. Farmers mainly adopt synthetic chemical molecules to control weeds, insect pests, and diseases. Different methods employed for weed/insect management in agriculture are depicted in Figure 1.

![Figure 1](image-url)  
**Figure 1.** Different weed/insect control methods used in agriculture.

The fuels used to operate the types of equipment involved in the applications of chemicals are mostly diesel and petrol. These commercial fuels are uneconomical for farmers in their day-to-day activities and contaminate the natural ecosystem due to toxic gas emissions. Apart from the spraying equipment, some devices such as light insect traps and fences are operated by electrical energy. Mostly electrical energy is not available in
isolated and remote agricultural farms, i.e., off-grid areas in general. Under such circumstances, electricity produced from the sunlight is the best option for un-electrified remote areas in tropical and subtropical countries due to abundant solar radiation. Solar energy has wide applications such as space heating/cooling, thermal applications for industries, cooking, distillation, refrigeration, water heating, electricity production, etc. [9]. The present paper envisages the recent developments and applications of solar-powered plant protection equipment.

2. Eco-Friendly Strategies for Plant Protection

Generally, plant protection involves management strategies for controlling insect pests, diseases, birds, and other biological stresses during crop cultivation. The concept of integrated pest management (IPM) involves cultural, physical, mechanical, behavioral, biological, and chemical methods. Among the current strategies, the chemical method is the most viable, effective, and readily available option in the crop production system. In many countries, synthetic pesticides are primarily used to control pests. However, improper use of synthetic chemical molecules directly affects agro-horticultural ecosystems and the environment, and they also contaminate harvested farm produce. Nowadays, chemical pesticides develop resistance in insects and pathogens, forcing farmers to use higher quantities and indiscriminate pesticides. Overuse of pesticides poses a high risk to the public who consume these products with residual pesticides and affects the existing natural environment [10]. Non-optimal use of pesticides leads to resistance and resurgence development in pests and diversity loss in the natural environment [11,12]. The management of insect pests has become one of the biggest challenges for organic cultivation, making new, eco-friendly alternative management strategies a timely need to combat the problems. Physical methods include electric and bait traps, which have received a great deal of attention worldwide [12,13]. Farmers are more interested in implementing eco-friendly pest management strategies and handling plant health management techniques at the right time during crop production. The preference is for management strategies and the delivery system or mode of implementing these methods. The utilization of eco-friendly energy sources might be the most preferred operating tool in plant protection if options are many. However, eco-friendly energies for various plant protection operations are a newer dimension of agriculture and organic farming. According to an FAO (2000) survey, 35 percent of solar energy is utilized in agricultural activities such as irrigation, livestock watering, and electric fencing. Only 2 percent is used for operating the sprayers, whereas power consumption for solar fencing protection against grazing animals is 14 percent.

3. Applications of Solar Energy in Agriculture

In the current situation, there is a timely need to substitute commercial energy usage with new eco-friendly energy sources in agriculture and reduce the negative impacts on the environment. Renewable energy sources are the right choice for biofuel and electricity to replace conventional energy sources. Electricity generation from solar and wind energy is well proven, and the technologies are already available, installed, and used worldwide.

Among the renewable energy sources, solar energy is closely associated with agriculture. Generally, the plant derives light energy from the sun for photosynthesis. In other words, plants produce their food by using water and CO₂ present in the atmosphere via photosynthesis in sunlight. Solar energy usage in agriculture is not a new technology in the post-harvest processing of agro produce. In earlier days, sunlight was directly used to dry different types of agro produce by spreading them in the open and then storing them for future use. In the case of solar thermal energy applications, conventional open-yard sun drying and solar drying are more popular among the farming community. The two forms of energy obtained from sun, light and thermal energy, can be tapped by using devices for various applications both at domestic and industrial levels in agriculture and agro/food processing sectors.
Many reviews on solar energy utilization in agriculture are found in the literature [14,15], including solar photovoltaic reviews [16–20] and PV economics and potential [21,22]. Different solar dryer designs, thermal energy backup systems, and various solar drying technologies have been well documented [15,23–43].

4. Solar PV Technologies

Electricity production using solar energy is achieved either through photovoltaic technology or the concentration of solar power [44]. However, the solar PV system is mainly preferred for a mobile/stationary machine that requires low power inputs. Solar PV technology uses the photovoltaic effect for converting sunlight into electrical energy. The electrical load should be connected either directly to the PV system or battery. The added advantages of PV are the lack of moving parts, power production on any scale, reliable power production without toxic gas emissions, and long lifespan. The most common PV applications include remote site electrification, street lights, traffic signals, vehicle battery charging, water pumping, fencing, communications, satellite, and remote monitoring [9,45]. Several reviews are published on the different aspects of solar PV water pumping [46–56] and design aspects of solar pumping [31,37]. There is a broad scope for the successful implementation of solar-powered farm machinery/tools/implements in agriculture. Popular PV-powered farm gadgets used in crop production include solar water pumping, solar fencing, solar-operated sprayers, solar-operated dusters, solar bird scarers, solar insect traps, and solar PV–thermal hybrid drying systems. Standalone solar PV is unique and has several potential applications in agriculture.

5. Solar-Powered Equipment for Weed Management

5.1. Solar Power Weeder

Weeds are usually eradicated by mechanical action or synthetic herbicides. Few herbicides are available with a specific mode of action, making it tedious to identify and achieve the expected management of weeds [57]. Mechanical weeding involves the repetitive actions of weeding tools (operated by man/machine) to make physical contact with weeds to uproot them [58]. Manual weeding is an energy- and labor-intensive process, and women laborers are primarily involved in manual weeding, which also increases the cost of operation. In order to reduce the drudgery and discomfort of the workers, long-handled weeder are available for both dry and wetlands. Presently, the utilization of human power has become expensive in developing countries such as India due to the non-availability of farm laborers or higher wage expectations. Developing fully or semi-automated weeders is mandatory in farm mechanization to reduce the labor force. Solar-powered weeders are an excellent alternative to implement sustainable mechanization in agriculture due to increased fuel costs.

The components of solar weeders are a solar panel, a rechargeable battery, transport wheels, a motor, weed detectors (sensors/cameras), and a weeding mechanism. Generally, lead acid batteries are preferred for these types of equipment. The added advantages of lead acid batteries are that they are inexpensive, have a long life cycle, have a higher energy density, a higher surge current supply, and a lower energy to weight ratio than other battery types [59]. These batteries are a viable option for a DC motor with higher torque for electric vehicles [59].

Solar robotic weeder are also available, and they work a minimum of five hours continuously, which helps control weeds in time. Most solar weeders are robotic models, and their weeding operations are either mechanical or chemical spray types. DC motors are used in the weeder for movement and mechanical weeding purposes. The added advantages of these models are reduced human resources, no fuel requirement, more precision in weeding, light weight, and 24/7 operations. Furthermore, the solar panel is attached to the system, which helps recharge the battery, even during operations. Generally,
12 V rechargeable batteries are used in solar-powered mechanical weeders. The number of batteries may vary based on the power requirement for its operation (Table 1).

**Table 1.** Different types of powered weeders.

| S. No | Particulars                                | Transport | Solar Power | Battery Specification | PV Panel Attachment | Power Used to                  | Reference |
|-------|--------------------------------------------|-----------|-------------|-----------------------|---------------------|--------------------------------|-----------|
| 1.    | Solar energy-based vehicle weed detecting robotic model | Wheels    | 20–40 W     | Rechargeable battery, 12 V, 7 Ah | Inbuilt             | DC motors (7 nos.)              | [60]      |
| 2.    | Greenbot—weeding                           | Wheels    | 100 W       | Rechargeable battery   | Inbuilt             | DC motors and other parts (3 nos.) | [61]      |
| 3.    | Prototype of solar weeding robot           | Wheel     | NA          | ---                   | --                  | DC motor and IR sensor          | [62]      |
| 4.    | Remote-Controlled Solar Agro Sprayer Robot (prototype) | Wheels    | NA          | 12 V battery (2 nos.) | --                  | DC motor and pumps              | [63]      |

The unmanned system (robot) is well suited for weeding operations, and it helps to minimize the required workforce and herbicide usage while weeding. Two solar-powered weeders, EcoRobot and AVO robot models, are developed by Ecorobotix, Switzerland (Figure 2). These models work more effectively in row crops based on the detection of weeds (>85%), and a micro-dose of herbicides is applied precisely on the weeds to destroy them. The solar power used in EcoRobot and AVO models is 380 W and 1150 W, respectively, and they have a working time of 8 and 12 h once fully charged by solar panels [64].

**Figure 2.** Solar-powered weeders [64].
6. Solar-Powered Equipment for Pest Management

6.1. Solar Insect Traps

Light traps are effective trapping tools for monitoring and managing insect pests [65,66]. These traps are also used for various scientific purposes, such as biodiversity analysis, taxonomic collections, periodic surveys, prediction of insect pest occurrence models, and monitoring [67,68]. The light trap consists of a light source, a holder with a dome, a funnel, vanes, a timer, an insect trapping system, and a stand. They are designed in different configurations based on the behavior of the insect’s response to the different wavelengths of light. For example, a mercury lamp emits a low-wavelength light, which lures a diversity of flying insects from the surrounding area. Preferred insect traps include flight-intercept traps [69], bait and pheromone traps [70], and traps that incorporate sticky surfaces [71]. Nocturnal insects tend to be attracted to a light source. This behavior is used in light traps. The insects hit the light or a vane and fall into the trap, and are killed or kept alive for monitoring [72].

Candescent bulbs were used in light traps in earlier days, which consumed more power and generated heat during operation. The power consumption increased the operational cost to the farmer. Nowadays, mercury vapor lamps, gas lamps, fluorescent lamps, ultra-violet (UV) fluorescent lamps, UV light-emitting diodes (LED) lamps, LED garden lamps, and compact fluorescent lamps (CFL) are used in light traps. Among them, the first three are predominantly used for pest management purposes [73]. However, LED bulbs are preferred in solar insect traps due to many features such as less energy consumption, low cost per unit trapping time, higher energy efficiency, longer lifespan, etc. Moreover, the specific wavelengths available in LED bulbs for particular insect species improve trapping efficiency [74–76].

Recently, solar light traps have become more popular among the farming community as they are cost-effective (Figure 3). The main components of these traps are similar to other electrical light traps except the battery, timer, and solar panel. A solar insect trap unit is exposed to sunlight during the daytime to generate and store electrical energy in the battery. A timer is another critical component in the light trap for operation. A stand is used to hold all parts of the trap at different heights according to the nature of crops. Several researchers developed and tested the details of solar insect light traps (Table 2). The energy required for the light source used in different solar insect traps ranges from 3 to 20 W. Mostly, 12 V rechargeable lead acid batteries are used in these traps. The wavelength of the light source used in the traps is 315 to 590 nm to attract different insect species. Common traps used to attract the insects are a container filled with a soapy solution, net structures, and glue boards [10,65,77–81]. Plastic cups/aluminum funnel traps with pheromone lures also trap insects for taxonomic studies [82–84]. When monitoring insects over an extended period, these kinds of solar light traps help to reduce the labor requirement due to automatic timers [85]. Solar light traps effectively attract pests in vegetable crops [10]. Calderon et al. [80] reported a unique LED light trap for rice bugs with a solar panel made of polycrystalline solar cells (20 W).
Table 2. Details of the solar insect traps tested for different crops.

| S. No. | Cropping System                  | Target Insects                                                                 | Light Source          | Battery Specification                  | Trapping System                                                                 | Solar Panel Power | Reference |
|-------|----------------------------------|--------------------------------------------------------------------------------|-----------------------|----------------------------------------|--------------------------------------------------------------------------------|--------------------|-----------|
| 1.    | Vegetable and coconut            | Leaf beetle, elephus beetle, aphids, leafhopper, leaf minor                    | UV LED bulb           | 12 V, 14 Ah, lead acid calcium battery | High-voltage circuit of mosquito wire net                                    | 20 W               | [10]      |
| 2.    | Veterinary—animal farms          | Tabanid fly                                                                    | LED                   | 12 V, 45 Ah, Lead acid battery         | -                                                                              | -                  | [86]      |
| 3.    | General vegetation               | Ground beetles, Calathus melanocephalus, Pseudoophonus rifipes                 | White LED bulb        | 1.2 V, 600 m Ah                       | Not mentioned                                                                  | -                  | [84]      |
| 4.    | Vegetation and cropped fields    | General insects                                                                | 12 W LED bulb         | 12 V, 7.5 Ah                          | Not mentioned                                                                  | 10 W               | [87]      |
| 5.    | Mango garden                     | Hemipteran and Dipteran insects                                                | 3 W UV LED bulb       | 12 V, 7 Ah sealed lead battery        | Wire mesh panel                                                                | 10 W               | [78]      |
| 6.    | Rice and Brinjal field           | General insects                                                                | UV lamp               | 12 V battery                          | Wire mesh panel                                                                | 10 W               | [79]      |
| 7.    | Plantation and Orchard crops     | General insects                                                                | 3 W DC lamp           | 12 V, 4.5 Ah rechargeable             | Mosquito net                                                                  | 25 W               | [65]      |
| 8.    | Annual crops                     | Spodoptera exigua, Heliothis assulta, Hemipteran bugs, green leafhopper, beetles, weevils, planthopper | 5 W DC lamp           | 12 V battery                         | -                                                                              | -                  | [74]      |
| 9.    | Rice                             | Black bug                                                                      | LED bulb              | 12 V polycrystalline solar cells      | Circuit of mosquito trap                                                       | 20 W               | [80]      |
| 10.   | Sweet potato                     | Sweet potato weevil                                                           | LED—Green light       | Battery-powered solar cell            | Pheromone funnel trap                                                         | -                  | [82]      |
| 11.   | Rice                             | Brown planthopper, yellow stem borer, pink stem borer, leaf folder, black bug | 20 W CFL              | -                                      | Container box for collecting pests with a solution of soap water               | -                  | [77]      |
| 12.   | General cropping area            | Herbivores                                                                     | 12 W UV fluorescent bulb | 12 V, 35 Ah rechargeable battery      | Aluminum funnel trap                                                          | 15 W               | [83]      |
| 13.   | Gardens with vegetation          | General insects                                                                | LED garden lamps      | 1.2 V, 600 mAh rechargeable battery  | Plastic cup as traps                                                          | -                  | [84]      |
| 14.   | Hayfield                         | Mosquito species                                                               | CDC light             | 6 V, 12 Ah UB6120 battery             | -                                                                              | 6 W                | [85]      |
15. - UV LED 12 V lead acid battery Cum/glue trap 10 W [81]

| 16. Rice | Rice leaffolder, *Tryporyza incertulas*, *Chilo suppressalis*, *Oxya chinensis*, gall midge, brown plant hopper | Different wavelength bulbs | - | - | - | [88] |

**Figure 3.** Solar insect light trap.

6.2. Solar-Powered Sprayers

Spraying is an operation of spreading fine droplets of liquid chemicals over plant canopy to protect them from pests and diseases. For this purpose, many versions of manual or power-operated (engine, battery, tractor, and power tiller) spraying equipment are used. Backpack, trolley type, and wheel-supported solar-powered sprayers are used as alternatives to conventional sprayers (Table 3). Solar PV sprayers consist of solar panels, rechargeable batteries, DC motors with a pump or a spinning disk, a chemical tank, wheels/support frame (based on types), a spray lance, and accessories. Solar panels are fitted in most of the sprayers for easy recharging. In the case of backpack sprayers, depending on the models, the power output from the solar panel varies in the range of 5 to 75 W. A solar-powered knapsack sprayer has a solar panel of 20 W, a 12 V and 7.5 Ah battery, a 12 V DC motor with a pump, a spraying tank, a frame, an adapter, and a connector output for multiple applications (radio, mobile charging, lighting, etc.). These kinds of sprayers are used for different crops such as cotton, red gram, and vegetables such as onion (Figure 4). The operation cost of solar-powered sprayers is INR 53.75, which is lower than battery-powered (INR 78.75) and manually operated (INR 102.5) sprayers.
| S. No. | Name of Sprayer                              | Device Movement       | Solar Power | Battery                                | Solar Panel | PV Power Used       | Reference |
|-------|-----------------------------------------------|-----------------------|-------------|----------------------------------------|-------------|---------------------|-----------|
| 1.    | Solar-powered semi-automatic pesticide sprayer | Transport wheels      | -           | Lead acid battery, 12 V, 7.5 Ah        | Inbuilt     | DC motor—pump       | [89]      |
| 2.    | Solar-powered sprayer                         | Backpack              | 5 W         | 12 V, 7 Ah                             | Stand alone | DC water pump       | [90]      |
| 3.    | Solar pesticide sprayer                       | Transportable trolley type | 5 W         | 12 V, 7 Ah                             | Inbuilt     | DC motor            | [91]      |
| 4.    | Solar PV backpack sprayer                     | Backpack              | 5 W         | Lead acid battery, 6 V, 4.5 Ah         | Inbuilt     | 6 V DC motor—spinning disc | [92]      |
| 5.    | Solar-powered sprayer                         | Backpack              | 5 W         | 12 V                                  | Inbuilt     | Solarized agro sprayer | [93]      |
| 6.    | Solar-powered knapsack sprayer               | Backpack              | 10 W        | 12 V                                  | Inbuilt     | DC motor pump       | [94]      |
| 7.    | Solar-based pesticide Sprayer                 | Backpack              | 10 W        | 12 V                                  | Inbuilt     | DC motor pump       | [95]      |
| 8.    | Solar-powered pesticide sprayer               | Backpack              | 20 W        | Lead acid battery 12 V, 8 Ah           | Stand alone | DC motor cum centrifuged pump | [96]      |
| 9.    | Solar-powered sprayer                         | Backpack              | 10 W        | 12 V, 7 Ah                            | Inbuilt     | DC motor            | [97]      |
| 10.   | Solar agro sprayer with night vision          | Backpack              | 10 W        | 12 V, 7 Ah                            | Inbuilt     | DC motor            | [98]      |
| 11.   | Multipurpose solar-powered sprayer            | Backpack              | 20 W        | 12 V, 7 Ah                            | Inbuilt     | DC motor—pump       | [99]      |
| 12.   | Wearable agricultural solar-powered sprayer   | Backpack              | 20 W        | Lead acid battery 12 V, 10 Ah          | Inbuilt     | DC motor—pump       | [100]     |
| 13.   | Solar-powered agricultural pesticide sprayer lab model | Backpack | 20 W     | Lead acid battery 12 V, 9 Ah          | Inbuilt     | Brushless DC motor—pump | [101]     |
| 14.   | Solar pesticide sprayer                       | Backpack              | 20 W        | polycrystalline                       | Inbuilt     | DC motor—pump       | [102]     |
| 15.   | Solar knapsack sprayer                        | Backpack              | 25 W        | Lead acid battery 12 V–9 Ah            | Inbuilt     | DC pump             | [103]     |
| 16.   | Solar-powered PV sprayer                      | Transport wheels      | 60 Wp (2 nos.) | 12 V, 7 Ah                            | Inbuilt     | DC pump—diaphragm pump | [104]     |
| No. | Description                                      | Type          | Power Source | Battery Type | Motor Type | References |
|-----|--------------------------------------------------|---------------|--------------|--------------|------------|------------|
| 17  | Solar-powered knapsack sprayer                   | Backpack      | 60 Wp        | Lead acid battery 7 Ah | Stand alone DC motor—pump set | [105] |
| 18  | Solar-powered sprayer                            | Backpack      | 60 W         | Lead acid battery | Stand alone DC motor—pump | [104] |
| 19  | Solar sprayer                                    | Backpack      | 75 W         | Lead acid 12 V, 7 Ah | Inbuilt DC motor—blower | [105] |
| 20  | Solar PV power sprayer                           | Trolley type  | 100 Wp polycrystalline (2 nos. × 50 W) | 12 V, 32 Ah | Inbuilt DC motor—pump of 60 W | [104] |
| 21  | Solar-powered high clearance sprayer             | Bullock drawn | -            | -            | -          | -          | [106] |
| 22  | Solar-powered microner sprayer                   | Lab model     | Polycrystalline silicon | Lead acid battery 12 V | Stand alone DC motor | [107] |
| 23  | Bullock-drawn solar-powered hi-tech sprayer      | Trolley type  | 500 W        | Dry lead acid 12 V,100 Ah | Inbuilt DC motor | [92] |
| 24  | Solar agro-remote controlled sprayer             | Wheel type    | -            | 12 V battery (2 nos.) | Stand alone DC motor—pump | [94] |
| 25  | Solar PV sprayer developed by NIPHM, Hyderabad   | Trolley       | -            | -            | Inbuilt/Stand alone DC motor—pump (60 W) | [108] |
| 26  | Remote-controlled solar agro sprayer robot (prototype) | Wheels     | NA           | 12 V battery (2 nos.) | -          | DC motor and pumps | [63] |
A solar PV sprayer consists of a DC pump (60 W), 60 Wp solar panels (2 nos.), a DC motor, batteries (2 nos., 12 V, 7 Ah), and a chemical tank (30 L). The area coverage and chemical application rate are 0.21 ha h\(^{-1}\) and 84 l h\(^{-1}\), respectively [109].
6.3. Solar PV Duster

A duster is a mechanical device used to apply solid chemicals in powder form to manage insect pests, weeds, and disease-causing pathogens in agro-horti ecosystems. The power source used for conventional dusters is either workforce or compression ignition engines. In a solar-powered duster, the main components are a solar panel, a rechargeable battery, and a dusting unit. Different types of solar-powered dusters employed in plant protection aspects are presented in Table 4. Electricity generation and storage are similar to other types of solar PV gadgets. The solar panel is fitted in a supporting frame, and it can be carried above the head of the operator without any weight on the head. The approach has two advantages: it provides shade to the operator, and charges the battery during operation. A battery-operated blower or a fan is used in the dusting unit to produce an air blast. The chemical powder from the hopper is sent to the blower outlet and carried by air to reach the exit point [110]. Furthermore, the device can be used for off-farm activities, such as lighting the house throughout the year when it is not in use as a duster/sprayer [109].

Table 4. Different types of solar-powered dusters.

| S. No | Name of the Equipment                  | Model         | Solar Power | Battery Specification | PV Panel Attachment | Power Used to                        | Reference |
|-------|---------------------------------------|---------------|-------------|-----------------------|---------------------|--------------------------------------|-----------|
| 1.    | Solar-powered multiple granulated pesticide duster | Lab model     | (Crystalline) 3 W | 6 V (3 nos.) | Inbuilt | DC motors for blower and feeding mechanism units | [111]     |
| 2.    | Solar-powered multiple granulated pesticide duster | Backpack      | 3 W         | Lead acid battery 6 V (3 nos.) | Inbuilt | DC motor                                      | [111]     |
| 3.    | Solar PV sprayer/dusters               | Backpack      | 6.5 W       | 12 V, 7 Ah            | Inbuilt | DC motor—rotating pump                        | [112]     |
| 4.    | Solar PV duster                        | Backpack      | -           | -                     | Inbuilt | Dusting unit                                  | [104]     |

Conventional and Solar-Based Plant Protection Equipment Methods

During the past three decades, conventional types of equipment have been primarily used in agricultural fields. Solar-powered plant protection equipment became one of the potential options for smart and sustainable organic agriculture. A comparison of conventional and solar-powered plant protection equipment is presented in Table 5. Solar-based equipment does not create any air pollution compared to the other types of equipment operated using fossil fuels. However, most solar-powered plant protection equipment, except solar insect traps and solar fencing, is in the research and development stage.
Table 5. Comparison of conventional and solar plant protection equipment.

| Particulars                              | Plant Protection Equipment (Sprayers) | Conventional | Solar |
|------------------------------------------|--------------------------------------|--------------|------|
| Power source                             | Manual, battery, compression ignition (CI engine (petrol or diesel) | Solar energy |
| Operational cost                         | Higher due to fuel price              | Nil          |
| Overall weight                           | Higher than solar PV sprayer         | Slightly less than CI engines |
| Training for operating machine           | Required                              | Required in case of drone sprayers |
| Cost                                     | Less                                  | Higher       |
| Power supply                             | Immediate after engine running       | Immediate after full charging of a battery |
| CO₂ emissions                            | Possible                              | No           |
| Mode of operation                        | The operator should carry the equip-  | The operator should carry the solar PV | |
|                                          | ment into an entire field             | sprayer into the entire field, whereas solar | |
|                                          |                                       | drone sprayers alone enter the field |
| Drift                                    | Less                                  | More in a drone sprayer due to its fan |
| Technology                               | Most of the machinery is commercial- | It is still under development and testing, not | |
|                                          | ized                                  | yet fully commercialized except for solar insect trap and solar fencing |
| Maintenance                              | Periodical cleaning of equipment re- | Periodic cleaning of the solar panel and | |
|                                          | quired and it may vary for different | checking the distilled water level in the bat- | |
|                                          | power sources                         | tery |
| Improvement point                        | Almost nil                            | Overall efficiency |
| Possible failure                         | Engine failure due to poor mainten-  | Battery failure due to poor maintenance |
|                                          | ance                                  | |

7. Solar-Powered Equipment for Non-Insect Pest Management

7.1. Solar Bird Scarer

Birds also cause considerable yield loss in agriculture and horticulture. During the grain filling, stage, or maturity stages of crops such as fruits, vegetables, and millets, birds such as parrots, pigeons, bulbul, myna, peacocks, and other vertebrate pests cause considerable damage to the crops. Even though birds may eat a tiny piece of the agro produce, the main problem is picking, spilling, and wasting while feeding, leading to considerable loss. Bird scaring is a simple technique to create an uncomfortable environment for birds and to disperse them from the target area [113]. Conventional methods are used to scare the birds, such as drumming, visual repellents (balloons, kites, plastic flagging, mylar streamers), busting crackers, flags, scarecrows, and whistling [114–118]. White cloth banging was used in paddy fields as a tactic to scare birds [119]. Chemical repellents are a socially acceptable, non-lethal approach to managing avian depredation of crops [120–123]. Gas cannons are also used to scare birds off crops, and they are most effective in combination with other scaring techniques [124]. Manual bird scaring, flags, and scarecrows can provide slight relief, which is ineffective for larger areas [125]. Moreover, they are labor-intensive and costly. Mechanical bird scarers can be a better option.

A solar bird scarer consists of a PV panel, a lead acid battery, an audio oscillator, an amplifier, and speakers [126]. Birds are scared by sounds produced in these units with different frequencies and pitches. Pande [126] suggested a wide range of frequencies to scare the birds for an extended period. A solar-powered bird repelling system consists of a solar panel (7 W, 12 V), a charge controller, a 12 V rechargeable battery, an MP3 player, an amplifier, speakers (2 × 20 W), three sonar sensors or PIR sensors, and an Arduino UNO microcontroller [127]. The MP3 player is used to play different sounds to scare the birds. A similar study was carried by Koyuncu and Lule [128] to test a bird scarer using an MP3 player of domestic birds’ predators’ calls to scare the birds and found that falcon was a
more aggressive sound than other predators. The results from Suryawanshi [113] confirmed the solar-powered audible bird scarer of Koyuncu and Lule [128]. Muminov et al. [127] also tested a solar-powered bird repelling system using bird scarer sounds. Another interesting study conducted by Siahaan et al. [129] using bird detectors and repellent via ultrasonic waves revealed that the frequency of 28–60 kHz could disturb bird activity on a farm.

7.2. Solar Fencing

Animals are other significant contributors to economic loss in agriculture, especially when farms are close to forest areas [130]. For example, wild animals such as elephants, gaur, sambar, and wild boar cause more crop loss in Kerala, India, whereas wild boars, monkeys, porcupines, goral, deer, and bears cause crop damage in central Italy and Nepal [131–133].

In remote areas, electric fencing is a proven technology to protect and safeguard fields from animals. Farmers may fail to protect their farms from animal attacks mainly due to the non-availability of electricity/absence of power grids. A PV electric fence is an alternative to the existing electric fence system and is well suited for off-grid areas. It is the most effective and economical approach for long-term operations in unelectrified areas. Solar PV fencing systems can fulfill farmers’ requirements to protect their crops (Figure 5). The components of the solar fencing system are solar panels, an energizer or a controller, a rechargeable battery, a main post, a fence wire supporting post, a t-post, a lightning diverter and choke kit, a super-earth kit, a super strain insulator, a permanent wire tightener, a chain wire strainer, tension springs, a double insulated lead-out cable, joint clamps, gateway and gates, cut out switches, electrified flood gates, live light, and a fence voltage alarm [134]. The current from the battery is supplied to the energizer to produce a high voltage with a low current in the fencing wires. Animals touching the fence wires experience a minimal electric shock which makes them leave the field. The fencing system would not cause any fatalities or injuries to animals/humans due to the low current supplied from the solar PV system. Kadam et al. [134] found that a combination of a solar panel (35 kW) and battery (12 V) was sufficient to effectively cover a 3.5 km fence line, which costs about USD 3300/km. In Kenya, 121 km of solar fencing was established to protect fields from elephant attacks in the West Laikipia area. The fencing system was arranged with 10 m spacing for fencing posts to support five fencing wires and 5 km spacing for an energizer house cum solar panels to produce 7 kV power [135]. Most solar PV-based fencing systems installed in South Africa were due to reduced costs compared to conventional fencing systems [136].

Figure 5. Solar fencing for agricultural field.

Schlageter and Haag-Wackernagel [137] studied the deterrence effect of solar blinkers for wild boars. The components of solar blinkers are red LEDs, a solar cell, an on/off switch, and an implied accumulator. During the operation, LEDs blink at the rate of 2 Hz,
and the light is visible for 500 m in the clear nighttime. They found that solar blinkers were insufficient for effective crop protection.

Bapat et al. [138] developed a wireless sensor network-supported farm intrusion detection system (FIDS) to protect crops from animal intrusions. This system consisted of PIR sensors, sound-generating devices, light flashers, and an RF module and was powered by the solar PV system. The FIDS was fixed at field boundaries to detect and stop animals.

8. Future Perspectives and Prospects

The performance of most fossil fuel- and electricity-based plant protection equipment is well documented, and their operational parameters are also optimized. The utilization of PV systems for different applications constitutes a new era in agriculture, horticulture, and forest sectors. A PV system is a potential alternative, offering more opportunities in operating different types of electricity-based agricultural equipment. The development of devices with simple construction/operation for plant production and protection may work well on small-scale farms and in post-harvest processing units. The efficiency details of various solar power-operated units are given in Table 6. Even though the applications and power requirements of plant protection equipment are different, the PV system’s overall performance needs to improve. The research on PV systems should be focused on improving their performance, such as solar panel efficiency, overall system efficiency, and enhanced battery life. The main areas to emphasize to improve the performance of PV-powered plant protection equipment (Figure 6) are as follows:

- The operating mechanism is an important deciding factor to finalize the size of the panel and the battery capacity to operate the machine. For instance, there are two common methods to eradicate weeds/insects, namely mechanical and chemical. Power requirements may be different for each of these methods.
- The improvement of solar panel efficiency results in a smaller panel size/area, and it indirectly results in an overall weight reduction of the system.
- The overall performance of the device ultimately depends on the performance of the battery. The battery capacity is directly linked to the size/weight of the battery. If the battery’s power density can be improved, the battery size will reduce while outputting the same power. Hence, it is suggested that battery life should be enhanced to reduce the maintenance cost. If all three requisites are fulfilled, an improvement in overall performance may be achieved.
- Sensors for image capturing of weeds/insects, sound detection, motion capturing of birds, and timers can be incorporated in the plant protection devices to improve their performance.
- The solar PV plant protection equipment with artificial intelligence (AI), remote sensing, and supporting software may minimize the required power and costs for their operations, resulting in better performance. For example, an integrated approach can be used for a drone-operated bird scarer cum sprayer (Figure 7). This would help in reducing the overall cost and can also be used for other purposes.
- The Internet of Things (IoT) has a potential purpose in agriculture, which would help in increasing the efficiency of agricultural production processes [139]. Applications of IoT technologies can modify existing agricultural practices [140]. Furthermore, IoT-supported automation of solar-powered plant protection equipment will reduce labor requirements with improved crop yield, which would lead to smart health monitoring in agriculture.
- Solar-powered plant protection equipment can be operational only for a few days or weeks in the entire crop duration (Table 7). The equipment will be idle when not used, and daily charging and discharging of the battery should be carried out for better utilization of the PV system. The battery in the PV system must be monitored regularly. Poor maintenance of the battery will lead to reduced battery life. In order
to avoid this situation, the PV system and battery may be used for off-farming activities.

- Recently, farmers have started using drone sprayers due to the simplicity of operation and more coverage per day. There is not much research on solar-powered drone-operated sprayers. Since drone sprayers require fans for their operation and air mass, nearby areas also would be affected by their operation. Moreover, there will be more chances for the drift of chemicals in the air. Future research may focus on the effective utilization of solar-powered drones with proper calibrations.
- The economic and technical feasibility studies for such solar equipment may be carried out before launching them into the commercial market.

Table 6. Efficiency of different solar-powered plant protection devices used in agriculture.

| Unit                                      | Specification                                      | Crop      | Efficiency (%) | References |
|-------------------------------------------|---------------------------------------------------|-----------|----------------|------------|
| Solar-powered knapsack sprayer            | Capacity: 20 L                                    | Egg plant | 77.00          | [103]      |
|                                           | Solar panel wattage: 25 W                          |           |                |            |
|                                           | Flow rate: 600 mL min⁻¹                             |           |                |            |
| Solar-operated walking-type power weeder  | Dimensions: 1260 × 960 mm                          | Groundnut | 90.24          | [141]      |
|                                           | Panel wattage: 150 W (2 Nos.)                      |           |                |            |
|                                           | Operational width: 35 cm                           |           |                |            |
|                                           | Weeding depth: 2–3 cm                              |           |                |            |
| Solar energy-operated paddy weeder        | Dimensions: 1450 × 950 × 700 mm                    | Paddy    | 83.30          | [142]      |
|                                           | Panel wattage: 160 W                               |           |                |            |
|                                           | Type: Cage wheel                                   |           |                |            |
|                                           | Depth of operation: 30–70 mm                       |           |                |            |
| Solar-operated power weeder               | Panel wattage: 160 W                               | Maize     | 88.03          | [143]      |
|                                           | Cutting width of blade: 70 mm                      |           |                |            |
|                                           | No. of blades: 4                                   |           |                |            |
| Solar-powered light-emitting diode insect trap | Dimension: 185 × 160 mm                           | Groundnut | 37.31          | [144]      |
|                                           | Panel wattage: 3 W                                 |           |                |            |
|                                           | Battery capacity: 10 Ah                            |           |                |            |

Table 7. Schedule of different PV-powered plant protection equipment used in agriculture.

| Name of PV Device | Sowing | Vegetative | Flowering | Maturity | Harvesting |
|-------------------|--------|------------|-----------|----------|------------|
| Solar bird scarer |        |            |           |          |            |
| Solar weeder      |        |            |           |          |            |
| Solar insect trap |        |            |           |          |            |
| Solar sprayer     |        |            |           |          |            |
| Solar duster      |        |            |           |          |            |
| Solar fencing     |        |            |           |          |            |

* stages may vary from crop to crop.
9. Conclusions

Presently, renewable energy sources are becoming popular and are effectively utilized in different sectors at domestic and industrial levels. Among them, solar-powered devices are booming, especially in tropical countries due to the availability of more solar radiation and low operational costs. Effective utilization of solar resources entails sustainable intensification and development in agriculture. We studied solar-powered equipment in agriculture, exclusively for plant health management in terms of crop protection aspects, and reviewed the advantages of solar-powered plant protection equipment such as light traps, bird scarers, fencing, sprayers, and dusters. Solar light traps and solar fencing, in particular, have recently become more popular among farmers.

Low-cost, solar-powered technology is the need of the hour to prevent crop loss, as these devices may be operated with less power, reduced battery weight, and lower costs,
with the incorporation of electronics for easy controlling and monitoring of operations for the benefit of the farming community. Several suggestions for solar-powered devices have been proposed to help farmers and entrepreneurs reduce the device operator’s burden. Moreover, PV-powered plant protection equipment will help promote sustainable agriculture with profitable returns in the future by eliminating the dependence on fossil fuels and associated environmental pollutions. Future studies can focus on developing new and innovative hybridization concepts of solar-powered equipment for profitable agriculture.

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**References**

1. Jha, G.K.; Pal, S.; Singh, A. Changing Energy-Use Pattern and the Demand Projection for Indian Agriculture. *Agric. Econ. Res. Rev.* 2012, 25, 61–68.
2. Scherm, H.; Sutherst, R.W.; Harrington, R.; Ingram, J.S.I. Global Networking for Assessment of Impacts of Global Change on Plant Pests. *Environ. Pollut.* 2000, 108, 333–341.
3. Van Lenteren, J.C. Ecosystem Services to Biological Control of Pests: Why Are They Ignored? *Proc. Sect. Exp. Appl. Entomol. - Neth. Entomol. Soc.* 2006, 17, 103. Available online: https://secties.nev.nl/pages/publicaties/proceedings/nummers/17/103-111.pdf (accessed on 4 October 2022).
4. Bridges, D.C. Crop Losses Due to Weeds in the United States, 1992; Weed Science Society of America: Westminster, UK, 1992; ISBN 0911733159.
5. Swinton, S.M.; Buhler, D.D.; Forcella, F.; Gunsolus, J.L.; King, R.P. Estimation of Crop Yield Loss Due to Interference by Multiple Weed Species. *Weed Sci.* 1994, 42, 103–109.
6. Boydston, R.A.; Mojtabehdi, H.; Crosslin, J.M.; Brown, C.R.; Anderson, T. Effect of Hairy Nightshade (Solanum Sarrachoides) Presence on Potato Nematodes, Diseases, and Insect Pests. *Weed Sci.* 2008, 56, 151–154.
7. Pimentel, D.; Peshin, R. Integrated Pest Management: Pesticide Problems; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2014; Volume 3, ISBN 9400777965.
8. Dhaliwal, G.S.; Koul, O.; Arora, R.; Cuperus, G.W. Integrated Pest Management: Retrospect and Prospect. In *Integrated Pest Management: Potential, Constraints and Challenges*; CABl Publishing; Wallingford, UK, 2004.
9. Kannan, N.; Vakeesan, D. Solar Energy for Future World—A Review. *Renew. Sustain. Energy Rev.* 2016, 62, 1092–1105.
10. Sermisi, N.; Torasa, C. Solar Energy-Based Insect Pest Trap. *Procedia-Soc. Behav. Sci.* 2015, 197, 2548–2553.
11. Kim, K.-N.; Song, H.-S.; Li, C.-S.; Huang, Q.-Y.; Lei, C.-L. Effect of Several Factors on the Phototactic Response of the Oriental Armyworm, Mythimna Separata (Lepidoptera: Noctuidae). *J. Asia-Pac. Entomol.* 2018, 21, 952–957.
12. Park, J.-H.; Lee, H.-S. Phototactic Behavioral Response of Agricultural Insects and Stored-Product Insects to Light-Emitting Diodes (LEDs). *Appl. Biol. Chem.* 2017, 60, 137–144.
13. Johansen, N.S.; Vänninen, I.; Pinto, D.M.; Nissinen, A.L.; Shipp, L. In the Light of New Greenhouse Technologies: 2. Direct Effects of Artificial Lighting on Arthropods and Integrated Pest Management in Greenhouse Crops. *Ann. Appl. Biol.* 2011, 159, 1–27.
14. Khan, J.; Arsalan, M.H. Solar Power Technologies for Sustainable Electricity Generation—A Review. *Renew. Sustain. Energy Rev.* 2016, 55, 414–425.
15. Mustaeyn, A.; Mekhilef, S.; Saidur, R. Performance Study of Different Solar Dryers: A Review. *Renew. Sustain. Energy Rev.* 2014, 34, 463–470.
16. El Chaar, L.; El Zein, N. Review of Photovoltaic Technologies. *Renew. Sustain. Energy Rev.* 2011, 15, 2165–2175.
17. Joshi, A.S.; Dincer, I.; Reddy, B. V Performance Analysis of Photovoltaic Systems: A Review. *Renew. Sustain. Energy Rev.* 2009, 13, 1884–1897.
18. Meral, M.E.; Dincer, F. A Review of the Factors Affecting Operation and Efficiency of Photovoltaic Based Electricity Generation Systems. *Renew. Sustain. Energy Rev.* 2011, 15, 2176–2184.
19. Parida, B.; Iniyan, S.; Goic, R. A Review of Solar Photovoltaic Technologies. *Renew. Sustain. Energy Rev.* 2011, 15, 1625–1636.
20. Singh, G.K. Solar Power Generation by PV (Photovoltaic) Technology: A Review. *Energy* 2013, 53, 1–13.
21. Foster, R.; Cota, A. Solar Water Pumping Advances and Comparative Economics. *Energy Procedia* 2014, 57, 1431–1436.
22. Meah, K.; Ula, S.; Barrett, S. Solar Photovoltaic Water Pumping—Opportunities and Challenges. *Renew. Sustain. Energy Rev.* **2008**, *12*, 1162–1175.

23. Bal, L.M.; Satya, S.; Naik, S.N. Solar Dryer with Thermal Energy Storage Systems for Drying Agricultural Food Products: A Review. *Renew. Sustain. Energy Rev.* **2010**, *14*, 2298–2314.

24. Chauhdhari, A.D.; Salve, S.P. A Review of Solar Dryer Technologies. *Int. J. Res. Advent Technol.* **2014**, *2*, 218–232.

25. Chauhan, P.S.; Kumar, A.; Tekasakul, P. Applications of Software in Solar Drying Systems: A Review. *Renew. Sustain. Energy Rev.* **2015**, *51*, 1326–1337.

26. Chauhan, Y.B.; Rathod, P.P. A Comprehensive Review of the Solar Dryer. *Int. J. Ambient Energy* **2020**, *41*, 348–367.

27. El-Sebaii, A.A.; Shalaby, S.M. Solar Drying of Agricultural Products: A Review. *Renew. Sustain. Energy Rev.* **2012**, *16*, 37–43.

28. Fudholi, A.; Sopian, K.; Ruslan, M.H.; Alghoul, M.A.; Sulaiman, M.Y. Review of Solar Dryers for Agricultural and Marine Products. *Renew. Sustain. Energy Rev.* **2010**, *14*, 1–30.

29. El Hage, H.; Herez, A.; Ramadan, M.; Bazzi, H.; Khaled, M. An Investigation on Solar Drying: A Review with Economic and Environmental Assessment. *Energy* **2018**, *157*, 815–829.

30. Kant, K.; Shukla, A.; Sharma, A.; Kumar, A.; Jain, A. Thermal Energy Storage Based Solar Drying Systems: A Review. *Innov. Food Sci. Emerg. Technol.* **2016**, *34*, 86–99.

31. Muhsen, D.H.; Khatib, T.; Nagi, F. A Review of Photovoltaic Water Pumping System Designing Methods, Control Strategies and Field Performance. *Renew. Sustain. Energy Rev.* **2009**, *13*, 835–844.

32. Patil, R.; Gawande, R. A Review on Solar Tunnel Greenhouse Drying System. *Renew. Sustain. Energy Rev.* **2016**, *56*, 196–214.

33. Phadke, P.C.; Walke, P.V.; Kriplani, V.M. Direct Type Natural Convection Solar Dryer: A Review. *Int. J. Adv. Res. Sci. Eng.* **2015**, *4*, 256–262.

34. Pirasteh, G.; Saidur, R.; Rahman, S.M.A.; Rahim, N.A. A Review on Development of Solar Drying Applications. *Renew. Sustain. Energy Rev.* **2014**, *31*, 133–148.

35. Prakash, O.; Kumar, A. Solar Greenhouse Drying: A Review. *Renew. Sustain. Energy Rev.* **2014**, *29*, 905–910.

36. Rawat, R.; Kaushik, S.C.; Lamba, R. A Review on Modeling, Design Methodology and Size Optimization of Photovoltaic Based Water Pumping. Standalone and Grid Connected System. *Renew. Sustain. Energy Rev.* **2016**, *57*, 1506–1519.

37. Shalaby, S.M.; Bek, M.A.; El-Sebaii, A.A. Solar Dryers with PCM as Energy Storage Medium: A Review. *Renew. Sustain. Energy Rev.* **2014**, *33*, 110–116.

38. Sharma, A.; Chen, C.R.; Lan, N.V. Solar-Energy Drying Systems: A Review. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1185–1210.

39. Sontakke, M.S.; Salve, S.P. Solar Drying Technologies: A Review. *Int. J. Eng. Sci.* **2015**, *4*, 29–35.

40. Thirugnanasambandam, M.; Iniyan, S.; Goic, R. A Review of Solar Thermal Technologies. *Renew. Sustain. Energy Rev.* **2010**, *14*, 312–322.

41. VijayavenkataRaman, S.; Iniyan, S.; Goic, R. A Review of Solar Drying Technologies. *Renew. Sustain. Energy Rev.* **2012**, *16*, 2652–2670.

42. Ndukwu, M.C.; Bennamoun, L.; Simo-Tagne, M. Reviewing the Exergy Analysis of Solar Thermal Systems Integrated with Phase Change Materials. *Energies* **2021**, *14*, 724.

43. Chock, R.Y.; Clucas, B.; Peterson, E.K.; Blackwell, B.F.; Blumstein, D.T.; Church, K.; Fernández-Juricic, E.; Francescoli, G.; Greggor, A.L.; Kemp, P. Evaluating Potential Effects of Solar Power Facilities on Wildlife from an Animal Behavior Perspective. *Conserv. Sci. Pract.* **2021**, *3*, e319.

44. Kalogirou, S.A. *Solar Energy Engineering: Processes and Systems*; Academic Press: Oxford, UK, 2013; ISBN 0123972566.

45. Aliyu, M.; Hassan, G.; Said, S.A.; Siddiqui, M.U.; Alawami, A.T.; Elamin, I.M. A Review of Solar-Powered Water Pumping Systems. *Renew. Sustain. Energy Rev.* **2018**, *87*, 61–76.

46. Chandel, S.S.; Naik, M.N.; Chandel, R. Review of Performance Studies of Direct Coupled Photovoltaic Water Pumping Systems and Case Study. *Renew. Sustain. Energy Rev.* **2017**, *76*, 163–175.

47. Chandel, S.S.; Naik, M.N.; Chandel, R. Review of Solar Photovoltaic Water Pumping System Technology for Irrigation and Community Drinking Water Supplies. *Renew. Sustain. Energy Rev.* **2015**, *49*, 1084–1099.

48. Gopal, C.; Mohanraj, M.; Chandramohan, P.; Chandrasekar, P. Renewable Energy Source Water Pumping Systems—A Literature Review. *Renew. Sustain. Energy Rev.* **2013**, *25*, 351–370.

49. Koner, P.K. A Review on the Diversity of Photovoltaic Water Pumping Systems. *Int. Energy J.* **2017**, *15*, 89-110.

50. Li, G.; Jin, Y.; Akram, M.W.; Chen, X. Research and Current Status of the Solar Photovoltaic Water Pumping System—A Review. *Renew. Sustain. Energy Rev.* **2017**, *79*, 440–458.

51. Periasamy, P.; Jain, N.K.; Singh, I.P. A Review on Development of Photovoltaic Water Pumping System. *Renew. Sustain. Energy Rev.* **2015**, *43*, 918–925.

52. Poompavai, T.; Koswalya, M. Control and Energy Management Strategies Applied for Solar Photovoltaic and Wind Energy Fed Water Water Pumping System: A Review. *Renew. Sustain. Energy Rev.* **2019**, *107*, 108–122.

53. Shinde, V.B.; Wandre, S.S. Solar Photovoltaic Water Pumping System for Irrigation: A Review. *Afr. J. Agric. Res.* **2015**, *10*, 2267–2273.

54. Sontake, V.C.; Kalamkar, V.R. Solar Photovoltaic Water Pumping System—A Comprehensive Review. *Renew. Sustain. Energy Rev.* **2016**, *59*, 1038–1067.
56. Wazed, S.M.; Hughes, B.R.; O’Connor, D.; Calautit, J.K. A Review of Sustainable Solar Irrigation Systems for Sub-Saharan Africa. Renew. Sustain. Energy Rev. 2018, 81, 1206–1225.
57. Duke, S.O. Why Have No New Herbicide Modes of Action Appeared in Recent Years? Pest Manag. Sci. 2012, 68, 505–512.
58. Machleb, J.; Peeteinatos, G.G.; Kollenda, B.L.; Andújar, D.; Gerhards, R. Sensor-Based Mechanical Weed Control: Present State and Prospects. Comput. Electron. Agric. 2020, 176, 105638.
59. Khan, S.U.-D.; Almutairi, Z.A.; Al-Zaid, O.S.; Khan, S.U.-D. Development of Low Concentrated Solar Photovoltaic System with Lead Acid Battery as Storage Device. Curr. Appl. Phys. 2020, 20, 582–588.
60. Sujaritha, M.; Annadurai, S.; Satheeshkumar, J.; Sharan, S.K.; Mahesh, L. Weed Detecting Robot in Sugarcane Fields Using Fuzzy Real Time Classifier. Comput. Electron. Agric. 2017, 134, 160–171.
61. Sujaritha, M.; Lakshminarasimhan, M.; Fernandez, C.J.; Chandran, M. Greentobot: A Solar Autonomous Robot to Uproot Weeds in a Grape Field. Int. J. Comput. Sci. Eng. 2016, 4, 1351–1358.
62. Patel, H.; Prajapati, A.; Maheshwari, R. Design & Implementation of Solar Weeding Robot for Cotton Field. Int. Res. J. Eng. Technol. 2018, 5, 4, 3295–3298.
63. Malani, H.; Nanda, M.; Yadav, J.; Purohit, P.; Didwania, K.L. Remote Controlled Solar Agro Sprayer Robot. In Proceedings of the International Conference on Information and Communication Technology for Intelligent Systems; Springer: Berlin/Heidelberg, Germany, 2017; pp. 513–518.
64. : Ecorobotix: https://www.Ecorobotix.Com/En/Avo-Autonomous-Robot-Weeder/ (accessed on 4 October 2022).
65. Reddy, M.R.N.; Annmika, S.G. Modelling and Optimization of Solar Light Trap for Reducing and Controlling the Pest Population. Int. J. Engineering 2015, 3, 224–234.
66. Augul, R.S.H.; Al-Saffar, H.H.; Mzhr, N.N. Survey of Some Hemipteran Species Attracted to Light Traps. Adv. Biore. 2015, 6, 122–127.
67. Baker, R.R.; Cook, L.M. Moths: Population Estimates, Light-Traps and Migration. In Case Studies in Population Biology; Manchester University Press: Manchester, UK, 1985, pp. 188–211.
68. Beck, J.; Linsenmair, K.E. Feasibility of Light-Trapping in Community Research on Moths: Attraction Radius of Light, Completeness of Samples, Nightly Flight Times and Seasonality of Southeast-Asian Hawkmoths (Lepidoptera: Sphingidae). J. Res. Lepid. 2006, 39, 18–37.
69. Hill, C.J.; Cormack, M. A New Design and Some Preliminary Results for a Flight Intercept Trap to Sample Forest Canopy Arthropods. Aust. J. Entomol. 1997, 36, 51–55.
70. Furzlong, M.J.; Pell, J.K.; Choo, O.P.; Rahman, S.A. Field and Laboratory Evaluation of a Sex Pheromone Trap for the Autodisemination of the Fungal Entomopathogen Zoophthora Radicans (Entomophthorales) by the Diamondback Moth, Plutella xylostella (Lepidoptera: Yponomeutidae). Bull. Entomol. Res. 1995, 85, 331–337.
71. Bacon, O.G.; Seiber, J.N.; Kennedy, G.G. Evaluation of Survey Trapping Techniques for Potato Tuberworm Moths with Chemical Baited Traps. J. Econ. Entomol. 1976, 69, 569–572.
72. Montgomery, G.A.; Belitz, M.W.; Guralnick, R.P.; Tingley, M.W. Standards and Best Practices for Monitoring and Benchmarking Insects. Front. Ecol. Evol. 2018, 6, 513.
73. Sheikh, A.H.; Bhandari, R.; Thomas, M.; Bunkar, K. Light Trap and Insect Sampling: An Overview. Int. J. Curr. Res. 2016, 8, 40868–40873.
74. Bae, S.-D.; Park, J.-O.; Mainali, B.; Kim, H.; Yoon, Y.; Lee, Y.; Cho, Y. Evaluation of Different Light Colors in Solar Trap as Attractants to Cereal and Legume Insect Pests. Adv. Biores. 2015, 85, 1–12.
75. de Medeiros, B.A.S.; Barghini, A.; Vanin, S.A. Streetlights Attract a Broad Array of Beetle Species. Rev. Bras. Entomol. 2017, 61, 74–79.
76. Mwanga, E.P.; Ngowo, H.S.; Mapua, S.A.; Mmbando, A.S.; Kaindoa, E.W.; Kifungo, K.; Okumu, F.O. Evaluation of an Ultraviolet LED Trap for Catching Anopheles and Culex Mosquitoes in South-Eastern Tanzania. Parasit. Vectors 2019, 12, 1–12.
77. Baehaki, S.E.; Iswanto, E.H.; Munawar, D. Relationship of Predators Flight and Rice Pests That Caught on the Light Trap of Solar Cell-CFL-20 Watt. Int. J. Entomol. Res. 2015, 27, 516–521.
78. Kumar, N. Development and Evaluation of Eco-Friendly Solar-Light Based Light Trap. Int. J. Pure Appl. Biosci. 2019, 7, 356–360. https://doi.org/10.18782/2320-7051.5587.
79. Thangalakshmi, S.; Ramanujan, R. Electronic Trapping and Monitoring of Insect Pests Troubling Agricultural Fields. Int. J. Emerg. Eng. Res. Technol. 2015, 3, 206–213.
80. Calderon, R.A. Solar Powered Rice Black Bug Light Trap. In Proceedings of the 6th International Conference on Advances in Science, Engineering and Technology, Manila, Philippines, 17–18 December 2017; pp. 17–18.
81. Brimapureeswaran, R.; Nivas, G.; Meenatchi, R.; Sujeetha, A.R.P.; Loganathan, M. Development of a New Solar Light Cum Glue Trap Model and Its Utilization in Agriculture. Int. J. Emerg. Technol. Innov. Eng. 2016, 2, 37–41.
82. McGuate, G.T. Green Light Synergistically Enhances Male Sweetpotato Weevil Response to Sex Pheromone. Sci. Rep. 2014, 4, 4499.
83. Longing, S.D.; Discua, S.A.; Cokendolpher, J.C. A Solar-Powered UV Light Trap for Long-Term Monitoring of Insects in Remote Habitats. Coleopt. Bull. 2018, 72, 140–144.
84. Eccard, J.A.; Scheffler, I.; Franke, S.; Hoffmann, J. Off-grid: Solar Powered LED Illumination Impacts Epigeal Arthropods. Insect Conserv. Divers. 2018, 11, 600–607.
115. Haque, A.K.M.F.; Broom, D.M. Experiments Comparing the Use of Kites and Gas Bangers to Protect Crops from Woodpigeon Damage. *Agric. Ecosyst. Environ.* 1985, 12, 219–228.

116. Marsh, R.E.; Erickson, W.A.; Salmon, T.P. Bird Hazing and Frightening Methods and Techniques (with Emphasis on Containment Ponds). 1991. https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1051&context=icwdmother (accessed on 4 October 2022).

117. Esipisu, I. Climate-Smart Kenyan Crop Hits a Setback—Hungry Birds. Thompson Reuters Foundation News, 2013–2015. https://newstrust.org/item/20130807112810-q5vwy8 (accessed on 4 October 2022).

118. Wang, Z.; Fahey, D.; Lucas, A.; Griffin, A.S.; Chamitoff, G.; Wong, K.C. Bird Damage Management in Vineyards: Comparing Efficacy of a Bird Psychology-Incorporated Unmanned Aerial Vehicle System with Netting and Visual Scaring. *Crop Prot.* 2020, 137, 105260.

119. Kiruba, S.; Mishra, B.P.; Stalin, S.I.; Jeeva, S.; Dhas, S. Traditional Pest Management Practices in Kanyakumari District, Southern Peninsula India. 2006. http://nopr.niscair.res.in/bitstream/123456789/6802/1/IJTK%205(1)%20(2006)%2071-74.pdf (accessed on 4 October 2022).

120. Avery, M.L.; Werner, S.J.; Cummings, J.L.; Humphrey, J.S.; Milleson, M.P.; Carlson, J.C.; Primus, T.M.; Goodall, M.J. Caffeine for Reducing Bird Damage to Newly Seeded Rice. *Crop Prot.* 2005, 24, 651–657.

121. Cummings, J.L.; Pochop, P.A.; Engeman, R.M.; Davis Jr, J.E.; Primus, T.M. Evaluation of Flight ControlR to Reduce Blackbird Damage to Newly Planted Rice in Louisiana. *Intl. Biodeterior. Biodegrad.* 2002, 49, 169–173.

122. Linz, G.M.; Homan, H.J.; Slowik, A.A.; Penry, L.B. Evaluation of Registered Pesticides as Repellents for Reducing Blackbird (Icteridae) Damage to Sunflower. *Crop Prot.* 2006, 25, 842–847.

123. Werner, S.J.; Linz, G.M.; Tupper, S.K.; Carlson, J.C. Laboratory Efficacy of Chemical Repellents for Reducing Blackbird Damage in Rice and Sunflower Crops. *J. Wildl. Manag.* 2010, 74, 1400–1404.

124. Stickley, A.R.; Andrews, K.J. Survey of Mississippi Catfish Farmers on Means, Effort, and Costs to Repel Fish-Eating Birds from Ponds. In Proceedings of the Fourth Eastern Wildlife Damage Control Conference, Madison, WI, USA, 25–28 September 1989; p. 39.

125. De Mey, Y.; Demont, M.; Diagne, M. Estimating Bird Damage to Rice in Africa: Evidence from the Senegal River Valley. *J. Agric. Econ.* 2012, 63, 175–200.

126. Pande, P.C. A Novel Solar Device for Dusting Insecticide Powder. In Proceedings of the National Solar Energy Convention, Vienna, Austria, 6–10 July 1998; University of Roorkie, Roorkie, India, 1998; pp. 117–122.

127. Muminov, A.; Jeon, Y.C.; Na, D.; Lee, C.; Jeon, H.S. Development of a Solar Powered Bird Repeller System with Effective Bird Scarer Sounds. In Proceedings of the 2017 International Conference on Information Science and Communications Technologies (ICISCT), Tashkent, Uzbekistan, 2–4 November 2017; 2017; pp. 1–4.

128. Koyuncu, T.; Lule, F. Design, Manufacture and Test of a Solar Powered Audible Bird Scarer. *Int. J. Agric. Biosyst. Eng.* 2009, 3, 345–347.

129. Shahaan, Y.; Wardijono, B.A.; Mukhlys, Y. Design of Birds Detector and Repellent Using Frequency Based Arduino Uno with Android System. In Proceedings of the 2017 2nd International conferences on Information Technology, Information Systems and Electrical Engineering (ICITISEE), Yogyakarta, Indonesia, 1–2 November 2017; IEEE: 2017; pp. 239–243.

130. Feuerbacher, A.; Lippert, C.; Kuenzang, J.; Subedi, K. Low-Cost Electric Fencing for Peaceful Coexistence: An Analysis of Human-Wildlife Conflict Mitigation Strategies in Smallholder Agriculture. *Biol. Conserv.* 2021, 235, 108919.

131. Peechi, T. Studies on crop damage by wild animals in kerala and evaluation of control measures. https://docs.kfri.res.in/KFRI-RR/KFRI-RR169.pdf (accessed on 4 October 2022).

132. Amici, A.; Serrani, F.; Rossi, C.M.; Priml, R. Increase in Crop Damage Caused by Wild Boar (*Sus Scrofa* L.): The “Refuge Effect”. *Agron. Sustain. Dev.* 2012, 32, 683–692.

133. Awasthi, B.; Singh, N.B. Status of Human-Wildlife Conflict and Assessment of Crop Damage by Wild Animals in Gaurishankar Conservation Area, Nepal. *J. Inst. Sci. Technol.* 2015, 20, 107–111.

134. Kadam, D.M.; Dange, A.R.; Khambalkar, V.P. Performance of Solar Power Fencing System for Agriculture. *J. Agric. Technol.* 2011, 7, 1199–1209.

135. Evans, L.A.; Adams, W.M. Fencing Elephants: The Hidden Politics of Wildlife Fencing in Laikipia, Kenya. *Land Use Policy* 2016, 51, 215–228.

136. Hayward, M.W.; Kerley, G.I.H. Fencing for Conservation: Restriction of Evolutionary Potential or a Riposte to Threatening Processes? *Biol. Conserv.* 2009, 142, 1–13.

137. Schlageter, A.; Haag-Wackernagel, D. Effectiveness of Solar Blinkers as a Means of Crop Protection from Wild Boar Damage. *Crop Prot.* 2011, 30, 1216–1222.

138. Bapat, V.; Kale, P.; Shinde, V.; Deshpande, N.; Shaligram, A. WSN Application for Crop Protection to Divert Animal Intrusions in the Agricultural Land. *Comput. Electron. Agric.* 2017, 133, 88–96.

139. Nizetić, S.; Solić, P.; González-de, D.-L.; Patrono, L. Internet of Things (IoT): Opportunities, Issues and Challenges towards a Smart and Sustainable Future. *J. Clean. Prod.* 2020, 274, 122877.

140. Shafi, U.; Muntaz, R.; Garcia-Nieto, J.; Hassan, S.A.; Zaidi, S.A.R.; Iqbal, N. Precision Agriculture Techniques and Practices: From Considerations to Applications. *Sensors* 2019, 19, 3796.

141. Kachhot, A.R.; Dulawat, M.S.; Vadher, A.L. Development of Solar Operated Walking Type Power Weeder. Agriculture Science and Green Energy 2021, 2, 30–41.
142. Sahu, G.; Raheman, H. Development of a Solar Energy Operated Weeder for Wetland Paddy Crop. *J. Renew. Energy Environ.* 2022, 9, 1–11.

143. Kumari, S.; Mehta, A.K.; Menna, S.S. Development and Performance Evaluation of Solar Operated Power Weeder. *Int. Res. J. Eng. Technol.* 2019, 6, 1340–1343.

144. Balamurugan, R.; Kandasamy, P. Effectiveness of portable solar powered light emitting diode insect trap: Experimental investigation in a groundnut field. *J. Asia-Pac. Entomol.* 2021, 24, 1024–1032.