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REVIEW OF SOLAR-POWERED AGRICULTURAL ROBOTS FOR SUSTAINABLE AND AUTOMATED FARMING: TECHNOLOGIES, LIMITATIONS AND RESEARCH GAPS

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Abstract: Field operations on small landholdings remain dominated by manual labour and small internal-combustion machinery, both of which carry rising operating costs and measurable environmental penalties. Agricultural robotics has consequently attracted sustained research attention, and a distinct strand of that work couples mobile robotic platforms to on-board photovoltaic generation so that field tasks can be executed without a fuel supply chain. This paper reviews the published literature on agricultural field robots with particular emphasis on solar-powered, remote-controlled and microcontroller-based platforms intended for small holdings, together with the mechanical implements — weeding, cutting and digging — that such platforms carry. The review is organised thematically rather than statistically: representative studies are grouped by power source, autonomy level, locomotion arrangement, communication technology and field task, and are then compared against a common set of criteria. The literature establishes that lightweight electric platforms reduce soil loading and exhaust emissions relative to tractor-scale machinery, that vision-guided weeding is technically mature at research level, and that modular tool carriers are a productive design direction. It also reveals persistent limitations: photovoltaic sizing and energy budgets are seldom reported in reproducible form, maximum-power-point tracking and adaptive power management are rarely implemented in low-cost designs, the behaviour of short-range radio links within standing crop is largely uncharacterised, and cost, durability and maintenance evidence from smallholder plots is scarce. Against this background the paper positions a proposed low-cost, solar-powered, radio-controlled multi-implement robot concept, identifying which reviewed gaps it addresses in principle and which remain open. No experimental validation of the proposed concept is claimed.

Index Terms - agricultural robotics, solar-powered robot, photovoltaic energy system, precision agriculture, remote-controlled robot, embedded microcontroller, weeding and tillage implements, smallholder mechanisation

I. INTRODUCTION

Agriculture is simultaneously a consumer of technologies developed elsewhere and a demanding application domain in its own right, and the automation of field operations has become one of the central engineering problems of the sector [1], [7]. Reviews of the field consistently identify three converging pressures: a requirement to raise output per unit of land and per unit of input, a shrinking and ageing agricultural labour force, and an obligation to reduce the environmental burden of production [3], [4], [7]. Robotic systems are attractive because they address all three at once — they substitute for scarce labour, they permit treatment at plant rather than field scale, and, when electrified, they decouple field work from liquid fuel [2], [22]. The economic case, however, has never been automatic. Pedersen *et al.* showed two decades ago that the feasibility of an agricultural robot depends less on its technical sophistication than on the ratio of its capital and maintenance cost to the labour it displaces [8], and that finding continues to shape which designs reach the field.

Manual field work carries costs that are easy to state but hard to price. Weeding, inter-row cultivation, cutting and shallow digging are repetitive, physically demanding and highly time-critical: the agronomic window within which an operation is effective is often only a few days wide, so a shortfall in available labour translates directly into yield loss rather than merely into delay. Sparrow and Howard note that the social and labour consequences of agricultural automation — including the displacement and the redistribution of skilled work — have received far less attention in the engineering literature than the technical questions, even though they largely determine adoption [7]. For operators, the same tasks are associated with sustained awkward posture and repetitive loading, which is one reason the removal of the human from the immediate working zone of a cutting or tilling implement is treated in the literature as a safety benefit and not only a productivity benefit [2], [7].

Fuel-powered machinery introduces a second class of cost. Conventional tractor-scale equipment imposes both an emissions burden and a mechanical one: the mass required for traction produces soil compaction, which degrades structure and infiltration and therefore feeds back into yield. This coupling between machine mass and soil damage is the explicit motivation for the lightweight-platform argument advanced by Grimstad and From, who designed the Thorvald II system around low ground pressure rather than around raw drawbar pull [18]. On the emissions side, Gonzalez-de-Soto *et al.* demonstrated that hybridising the powertrain of a robotic tractor materially changes its pollutant profile [33], while Gorjian *et al.* and Ghobadpour *et al.* have surveyed the broader shift toward solar-powered and renewable-driven agricultural machinery as a route to farm-level energy independence [22], [23]. Taken together, these studies frame electrification not as a substitution of one energy carrier for another but as an enabler of a different machine architecture — smaller, lighter and more numerous.

Renewable generation is a natural partner for this architecture. A field robot performing light cultivation tasks demands power on the order of tens to hundreds of watts rather than tens of kilowatts, which places it within reach of on-board photovoltaic (PV) generation combined with electrochemical storage [22], [24], [26]. Ghobadpour *et al.* have analysed the sizing problem formally, optimising the split between PV, battery and range-extending sources for an agricultural mobile robot and showing that the working cycle — not the peak load — governs the design [24]. Chand *et al.* demonstrated a PV-powered, battery-buffered platform combining computer vision with irrigation and spraying functions [26], and Poojari *et al.* carried out structural and computational design of a solar-powered multifunctional platform intended for seed sowing and soil operations [27]. The concept of a solar-driven field robot is therefore well established in the literature; what remains contested is how such systems should be dimensioned, controlled and costed for the smallest farms.

The development of agricultural field robots itself has a long research lineage. Early work concentrated on perception and guidance for mechanical weed control [10]–[12]; platform-level engineering followed, with systematically designed weeding vehicles [36] and autonomous navigation demonstrated in sugar-beet rows [13]. Research platforms such as BoniRob established the field-robot-as-instrument-carrier paradigm for plant-level phenotyping [17], the RHEA project scaled the idea to heterogeneous fleets for crop protection [19], and Thorvald II generalised it into a re-configurable modular tool carrier [18]. Parallel strands addressed species-specific weed management [14], in-row weeding in vegetables [15], multi-robot coverage [16], integrated aerial–ground systems [20] and selective harvesting of high-value crops [21]. Recent surveys of actuators, sensors and perception subsystems indicate that the component technologies are no longer the binding constraint [6], [34], [35].

Between full autonomy and manual operation lies a band of tele-operated and semi-autonomous designs that is disproportionately represented in work aimed at small farms. Here the operator retains supervisory and navigational control through a wireless link while the machine performs the physically hazardous or fatiguing action. Ranjitha *et al.*, for example, describe a solar-powered multipurpose platform commanded from a hand-held application over a short-range wireless link and performing sowing, cutting and spraying [28]. This class of system trades throughput and unattended operation for a large reduction in sensing, computation and verification cost, which is precisely the trade a smallholder budget favours. It also raises questions the autonomy literature does not answer, notably how radio links behave inside a standing canopy [29], [30].

The motivation for reviewing solar-powered agricultural robots specifically, rather than agricultural robots in general, is a question of fit. Most of the world's farms are small holdings [9], frequently without dependable grid supply, for which tractor-scale automation is neither affordable nor physically appropriate. A compact, solar-charged, remotely commanded platform capable of exchanging implements between cutting and digging duties is a plausible answer to that combination of constraints — but the published evidence supporting the claim is unevenly distributed, with detailed engineering in some subsystems and near-silence in others.

This paper therefore has four objectives. First, it organises the literature on agricultural field robots into a comparative framework spanning power source, autonomy, locomotion, communication and field task. Second, it reviews in detail the technologies that recur in solar-powered, microcontroller-based designs. Third, it analyses the reviewed systems critically and extracts research gaps that are traceable to specific published evidence rather than to assumption. Fourth, it positions a proposed solar-powered agricultural robot concept — documented in a separate project synopsis and reproduced here only as a design proposal — against those gaps, distinguishing throughout between what the literature has demonstrated and what the proposal merely intends. Section II describes the review method; Sections III to VII present the review; Sections VIII and IX develop the critical analysis and gap statement; Sections X to XIII discuss the proposed concept, its relationship to the literature and future directions.

II. REVIEW METHODOLOGY

This paper is a thematic, critical narrative review. It is explicitly not a systematic review in the PRISMA sense: no exhaustive database enumeration was performed, no screening flow was recorded, and consequently no claim is made here about the total number of papers screened or the completeness of coverage. The objective was analytical rather than bibliometric — to characterise the design space of solar-powered and remotely controlled agricultural field robots and to locate defensible gaps in it.

2.1 Research themes

Six themes structured the search and the subsequent synthesis: (i) agricultural field robotics as a discipline, including its economics and its ethics; (ii) renewable, and specifically photovoltaic, energy supply for agricultural machinery; (iii) locomotion and chassis design for soft, uneven ground; (iv) agricultural implements integrated onto robotic platforms, with emphasis on weeding, cutting and digging; (v) embedded control architectures and wireless command links; and (vi) autonomy, from tele-operation through supervised operation to full autonomous navigation.

2.2 Types of source considered

Priority was given to peer-reviewed journal articles from established publishers — Elsevier, Springer, MDPI, Wiley and IEEE — and to full papers in indexed conference proceedings. Review and survey articles were used to establish the shape of the field and to identify primary sources [1]–[6], [22], [23], [25], [31], [32], [34], [35]. Primary engineering papers were used for claims about specific platforms and subsystems. Sources whose bibliographic details could not be independently confirmed were excluded, as were sources reporting performance figures without a stated measurement procedure.

2.3 Technologies reviewed and comparison criteria

Each retained system was characterised, where the source permitted, along nine dimensions: energy source and storage; power conditioning and energy management; locomotion and steering arrangement; the agricultural implement carried; the control platform; the communication technology and its reported range; the level of autonomy; the principal reported contribution; and the principal reported limitation. Cost and scalability were recorded as a tenth dimension wherever the source addressed them, though as Section VIII shows this was rarely the case. Table 1 sets out the criteria applied under each dimension.

Table 1. Thematic dimensions and comparison criteria applied in this review.

Dimension	Comparison criteria applied
Energy source	Generation type; whether photovoltaic array rating is reported; presence and type of storage; whether an energy budget or working-cycle analysis is given
Power management	Charge-control strategy (unregulated, on–off, or maximum-power-point tracking); regulation of logic and actuator rails; any duty-cycle or load-shedding logic
Locomotion	Number and arrangement of driven wheels or tracks; steering method; ground pressure or mass where stated; terrain on which the platform was operated
Agricultural implement	Operation performed (weeding, cutting, mowing, digging, ploughing, sowing, spraying); actuation of the implement; whether implements are interchangeable
Control platform	Class of controller (8-bit microcontroller, single-board computer, industrial controller); on-board sensing; software environment where reported
Communication	Physical layer and band; reported or claimed range; whether range was measured in crop; behaviour on link loss
Autonomy level	Tele-operated, semi-autonomous (operator-supervised), or fully autonomous; localisation method where autonomous
Contribution	The specific advance the authors claim, expressed in terms of capability rather than numerical performance
Limitation	Constraints stated by the authors themselves, plus constraints evident from the reported design

2.4 Limitations of this review

Three limitations should be stated plainly. First, the thematic method admits selection bias: systems reported in widely indexed venues are over-represented relative to the large body of regionally published undergraduate and postgraduate project work on solar agricultural robots, even though the latter is where most low-cost designs appear. Second, comparison across sources is constrained by heterogeneous reporting; several dimensions in Table 1 are simply absent from many primary papers, and the review records this absence rather than interpolating values. Third, and specific to the present work, the project synopsis that motivates Section X was accompanied by a short preliminary reference list of three items on solar-powered farm robots. Those entries could not be matched to verifiable indexed records with the bibliographic detail given, and the quantitative claims attached to them in the synopsis — figures for labour reduction, battery charging time, cost saving relative to manual methods, achievable radio range and field runtime — are therefore treated as unverified and are *not* reproduced or relied upon anywhere in this review. Where a verifiable published system closely matching one of those descriptions was located, it is cited directly instead [26]–[28]. All numerical and performance statements in this paper are attributed to sources whose bibliographic details were confirmed.

III. AGRICULTURAL ROBOTICS: AN OVERVIEW

3.1 Scope and definitions

Bechar and Vigneault define the agricultural field robot functionally, as an integration of sensing, reasoning, locomotion and end-effector subsystems capable of executing an agricultural operation in an unstructured outdoor environment [1]. Their two-part treatment is useful precisely because it separates components from operations: the first part analyses the subsystems, the second the tasks and the system-level integration required to perform them [1], [2]. The distinguishing feature of the agricultural case, relative to industrial robotics, is variability — in illumination, in terrain, in plant geometry and in the object of manipulation itself, which is alive and non-rigid.

3.2 Field robots and mobile platforms

Field robots are conventionally grouped by the function of the platform. One family treats the vehicle as an instrument carrier whose purpose is to deliver sensors to plants, exemplified by BoniRob and its multi-sensor phenotyping payload [17]. A second treats it as an implement carrier, replacing the tractor in a specific operation; the systematically designed weeding platform of Bakker *et al.* belongs here [36], as does the modular Thorvald II, which was explicitly conceived as a generic tool carrier re-configurable with hand tools between open-field, polytunnel and greenhouse geometries [18]. A third family distributes the work across several small machines, either as a heterogeneous ground-and-air fleet [19], [20] or as a homogeneous team sharing coverage of one field [16]. Reviews by Oliveira *et al.* and Fountas *et al.* map these families onto the operations they serve, from seedbed preparation through plant treatment to harvest and phenotyping [4], [5].

3.3 The autonomy spectrum

Autonomy in this domain is better treated as a continuum than as a binary property. At one end are fully autonomous platforms that localise themselves, plan coverage and execute treatment without intervention; Bakker *et al.* demonstrated autonomous navigation in sugar-beet rows [13], and the RHEA fleet coordinated multiple autonomous vehicles under a supervisory base station [19]. In the middle sit supervised or semi-autonomous systems in which the machine executes a bounded behaviour — row following, for instance — while an operator retains authority. At the other end are tele-operated platforms in which all navigational decisions remain with the operator and the machine contributes only actuation [28]. Roshanianfard *et al.* and Rondelli *et al.* trace how research emphasis has migrated along this spectrum over several decades [31], [32]. Importantly, the migration has not been monotonic at the low-cost end: work targeting affordability continues to favour tele-operation, because sensing and verification, not actuation, dominate the cost of autonomy [8].

3.4 Remote-controlled agricultural robots

Tele-operated agricultural platforms are usually built on a short-range radio or Bluetooth link to an embedded controller that decodes discrete commands and drives motor bridges [28]. The attraction is architectural simplicity: no localisation, no perception pipeline, no safety-critical decision logic on board. The corresponding weakness is that the operator must maintain line of sight or accept degraded control, and that the link itself becomes a single point of failure whose behaviour in a crop canopy is seldom characterised. Studies of wireless technology for agricultural deployment show that propagation in vegetation is strongly attenuating and frequency-dependent, which is one reason low-power wide-area technologies have displaced short-range links for telemetry applications [29], [30] — though not, so far, for latency-sensitive direct motion control.

3.5 Precision agriculture and the benefits of robotic field work

The agronomic rationale for field robotics is precision: the ability to sense and act at the scale of the individual plant rather than the management zone. Bawden *et al.* implemented species-specific weed management on a single platform, choosing a treatment per plant rather than per field [14]; Utstumo *et al.* achieved in-row weed control in vegetables, addressing the zone that mechanical implements cannot reach without damaging the crop [15]; and the RHEA programme showed that fleet-scale patch treatment can substitute for uniform application [19]. The reported benefits across this literature are consistent in kind: reduced chemical and water input through targeting, reduced soil loading through lower machine mass [18], removal of the operator from hazardous working zones [2], [7], and the possibility of operating outside the constraints of a human working day [4]. Fig. 1 summarises the classification framework used in the remainder of this review.

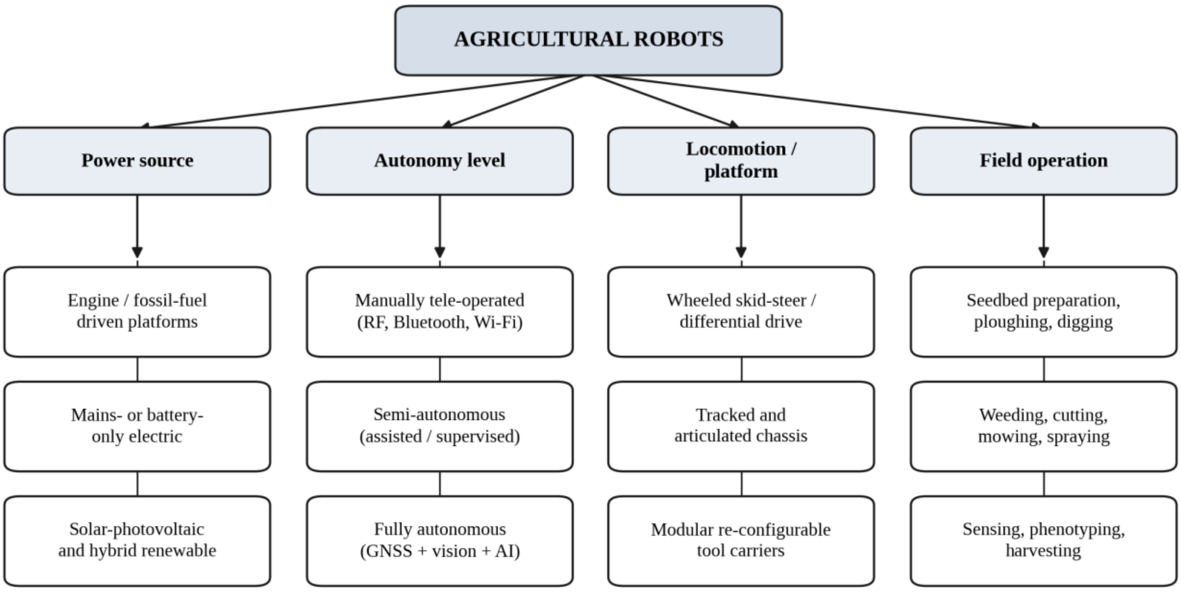

Fig. 1. Conceptual review figure: classification of agricultural robots by power source, autonomy level, locomotion arrangement and field operation, synthesised from the reviewed literature. The figure is an organising framework, not an experimental result.

IV. SOLAR-POWERED AGRICULTURAL ROBOTS

4.1 Solar energy in agricultural automation

The case for photovoltaic supply in agricultural machinery rests on a coincidence of scale. Gorjian *et al.* review the emergence of solar-powered electric agricultural machinery and identify light field operations as the natural first application, because their power demand falls within the range that a modest array and a practical battery can serve [22]. Ghobadpour *et al.* place this within a broader account of renewable-driven off-road vehicles and note that farms are unusual among industrial sites in having both large unshaded surfaces and a predictable seasonal correlation between solar availability and operational demand [23], [25]. The literature is nonetheless careful to distinguish two quite different configurations: stationary generation used to charge machines between tasks, and on-board generation intended to extend the working period during a task. The engineering constraints differ sharply, and several published designs are ambiguous about which they implement.

4.2 Photovoltaic subsystems

On-board PV is limited by projected area. A compact field robot offers a horizontal footprint of a fraction of a square metre, which bounds instantaneous generation well below the demand of simultaneous locomotion and implement actuation. The consequence, evident across the reviewed designs, is that the array does not power the robot directly during work; it replenishes storage over a longer interval than the interval of use [24], [26]. Chand *et al.* report this structure explicitly for their multi-purpose farming robot, in which the PV panel maintains a battery that in turn serves the vision system, controller and actuators [26]. Ghobadpour *et al.* formalise the resulting sizing problem, using optimisation over realistic working cycles to determine how PV, battery and a range-extending source should be proportioned; their central finding — that the duty cycle rather than the peak load determines the design point — is the most directly applicable result in this literature for anyone dimensioning a small solar platform [24].

4.3 Battery storage

Storage is the component that determines what a solar field robot can actually do in a session. The reviewed systems predominantly report sealed lead-acid or lithium-based packs, with the choice driven by cost in the low-end designs and by energy density in the research platforms [22], [25], [26]. Two properties matter more than nominal capacity. The first is usable depth of discharge, which for lead-acid chemistry is a fraction of the rating if cycle life is to be preserved, so that nameplate capacity systematically overstates available energy. The second is the current the pack can deliver during transients — implement engagement, stall recovery, starting under load — which for small packs can be the binding constraint rather than energy. Reporting on both points is thin in the reviewed low-cost literature, a gap taken up in Section VIII.

4.4 Charging and energy management

Energy management separates the research platforms from the low-cost designs more sharply than any other subsystem. At the sophisticated end, Ghobadpour *et al.* implement optimisation-based source allocation across a hybrid PV, fuel-cell and battery architecture, and elsewhere apply operation-recognition strategies to match power flow to the recognised farm task [24], [25]. Maximum-power-point tracking is standard in this class of work because PV output varies continuously with irradiance and cell temperature, and a fixed-voltage connection forfeits a substantial fraction of available energy. At the low-cost end, by contrast, published designs commonly connect the array to the battery through simple on–off or diode-isolated charge control and regulate only the logic rail [27], [28]. This is defensible on cost grounds but it has a consequence that is rarely acknowledged: without tracking, and without any load-shedding logic, the available working period becomes a function of weather that the system neither measures nor reports.

4.5 Advantages

The advantages attributed to solar-powered agricultural robots in the reviewed literature fall into four groups. Operationally, they remove the fuel supply chain from the field, which matters most where distribution is unreliable [22], [23]. Environmentally, they eliminate local combustion emissions, and — because PV supply pushes designers toward small, light platforms — they reduce the soil loading associated with tractor-scale mechanisation [18], [33]. Economically, they shift expenditure from recurring fuel cost to non-recurring capital cost, a shift whose desirability depends on the discount rate a smallholder faces and which the literature has not resolved [8]. Architecturally, low-voltage DC supply simplifies integration with embedded controllers and motor drivers, which is why the class is so accessible to small-scale development [26]–[28].

4.6 Limitations

The limitations are equally systematic. Generation is weather- and season-dependent and is reduced exactly when field work is most urgent after rain. Array area is bounded by the platform footprint, and increasing it raises the centre of mass and the wind loading on a machine that must remain stable on uneven ground. Storage adds mass, which increases traction demand and therefore consumption, producing a coupling between payload, traction and energy that the reviewed low-cost literature does not formalise. Implement power is the hardest constraint: cutting and especially digging demand torque and sustained current far in excess of locomotion, so an implement-carrying solar robot is dimensioned by its heaviest operation rather than by its average one. Table 2 compares the principal supply options against these considerations.

Table 2. Comparison of power-supply options for small agricultural field robots, compiled from the reviewed literature.

Attribute	Engine-driven (petrol/diesel)	Grid-charged battery only	On-board photovoltaic with battery	Hybrid photovoltaic with second source
Energy availability in field	High and independent of weather, limited only by fuel carried	Fixed by pack capacity; requires return to a charging point	Replenished during daylight; constrained by irradiance and array area	Sustained; second source covers low-irradiance periods
Recurring cost	Continuous fuel and servicing cost	Electricity cost; battery replacement	Negligible fuel cost; battery replacement	Low but non-zero; depends on second source
Capital cost	Moderate	Moderate	Higher than battery-only owing to array and charge control	Highest of the four
Local emissions	Combustion emissions at point of use [33]	None at point of use	None at point of use [22]	Depends on second source
Typical mass and soil loading	High; associated with compaction concerns [18]	Moderate	Moderate; array adds little mass but raises centre of mass	Moderate to high

Attribute	Engine-driven (petrol/diesel)	Grid-charged battery only	On-board photovoltaic with battery	Hybrid photovoltaic with second source
Control complexity	Low electrical complexity	Low; single regulated bus	Moderate; charge control and, where implemented, MPPT [24]	High; requires an energy-management strategy [24], [25]
Suitability for small holdings	Poor — scale and cost mismatch	Moderate where reliable supply exists	Good for light, intermittent operations	Limited by cost and maintenance burden
Representative sources	[33]	[18], [25]	[22], [26]–[28]	[24], [25]

V. REVIEW OF EXISTING AGRICULTURAL ROBOT SYSTEMS

This section groups representative studies by their defining characteristic. Because many systems belong to more than one category, each is discussed where its principal contribution lies and cross-referenced elsewhere.

5.1 Solar-powered agricultural robots

The most fully documented solar platform in the reviewed set is the multi-purpose smart farming robot of Chand *et al.*, which combines PV generation and battery storage with computer vision and Internet-of-Things connectivity to automate water sprinkling and pesticide spraying [26]. Its contribution is the integration itself: earlier solar farm machinery had been essentially unintelligent, applying water or chemical on operator command, whereas this platform makes the application decision from sensed plant and soil state. Its limitations, acknowledged in part by the authors, concern the dependence of the vision pipeline on illumination and the constraints that a PV-battery budget imposes on continuous operation. Poojari *et al.* approach the problem from the mechanical side, performing computational structural analysis of a solar-powered multifunctional platform carrying sowing, digging and ploughing mechanisms [27]; this is one of the few studies in the low-cost class to treat chassis stress and deformation quantitatively, but it correspondingly says little about control or energy management. At platform level, Ghobadpour *et al.* provide the most rigorous energy treatment, optimising source sizing for a PV-supplied agricultural mobile robot over realistic working cycles [24]. Across the three, a pattern is visible: individual subsystems have been treated well, but rarely in the same paper, and almost never together with cost.

5.2 Autonomous agricultural robots

Autonomous platforms are the best-documented category. Bakker *et al.* demonstrated autonomous navigation of a purpose-built platform in a sugar-beet field, having first derived the platform systematically from the weeding requirement rather than adapting existing machinery [13], [36]. BoniRob established a durable template for the autonomous instrument carrier, combining four-wheel independent drive with multi-sensor fusion and RTK-corrected satellite positioning for plant-level phenotyping [17]. The RHEA project extended autonomy to coordinated fleets of ground and aerial vehicles for weed and pest control under a supervisory base station [19], and Pretto *et al.* reported an integrated aerial–ground system for precision farming designed for adaptability across crops and sites [20]. McAllister *et al.* addressed the complementary question of how a team of small autonomous machines should divide coverage of a field [16]. The strengths of this category are unattended operation and repeatable treatment quality; the limitations are cost, dependence on positioning infrastructure, and the difficulty of certifying safe behaviour in an environment shared with people and animals [7].

5.3 Remote-controlled agricultural robots

Remote-controlled designs dominate work aimed at affordability. Ranjitha *et al.* report a solar-powered multipurpose robot commanded over a short-range wireless link from a hand-held application, performing seed sowing, grass cutting and pesticide spraying with an 8-bit microcontroller coordinating motor drivers [28]. The strengths are directness and cost: the operator supplies perception and judgement, so the machine needs neither. The limitations are equally direct. Control range and reliability are set by the radio link, and the reviewed papers in this class do not report link-budget measurements in standing crop; the wireless literature indicates that vegetation attenuation is substantial and frequency-dependent [29], [30], so range figures obtained in the open are not transferable. Nor do these papers generally specify the behaviour of the platform on loss of link — a safety-relevant omission when a rotating cutter is engaged.

5.4 Weeding robots

Weeding is the most intensively studied agricultural robotic operation and the category with the deepest methodological literature. Slaughter *et al.* surveyed the four subsystems on which any autonomous weed-control system depends — guidance, detection and identification, precision in-row actuation, and mapping — and their analysis remains the standard framing of the problem [10]. Åstrand and Baerveldt demonstrated a vision-guided mobile robot performing mechanical weed control, combining row following with individual weed detection [11], while Blasco *et al.* pursued machine-vision-directed weed control in the same period [12]. Later work sharpened the actuation: Bawden *et al.* built a platform capable of applying different treatments to different weed species [14], and Utstumo *et al.* attacked in-row weeding in vegetables, the hardest case because implements cannot pass between crop plants without damage [15]. The strength of this body of work is that plant-level discrimination and treatment have been convincingly demonstrated. What remains unresolved is transfer: the systems are largely research platforms whose sensing and computation costs sit far above the reach of a smallholder, and their energy demands are not reported in a form that would support solar dimensioning.

5.5 Cutting and crop-management robots

Cutting, mowing and topping operations receive less dedicated attention in the indexed literature than weeding, and appear most often as one function among several on multipurpose platforms [27], [28]. Where cutting is treated seriously, it is generally as an actuation and safety problem rather than a perception problem: the implement is a high-inertia rotating mass whose engagement transient dominates the electrical load and whose exposure dominates the hazard analysis. Reviews of agricultural actuators and sensors note that implement actuation and its control have received markedly less research attention than navigation and perception [34], [35], and the cutting case illustrates the point: papers that specify a cutting mechanism seldom report the torque or current it draws, which is precisely the datum a solar-powered design needs.

5.6 Soil digging and ploughing robots

Digging, furrowing and shallow tillage are the most demanding operations attempted by small robotic platforms, because the reaction force is transmitted through the chassis to the wheels and must be resisted by traction. Poojari *et al.* address this directly, analysing chassis deformation and stress for a platform carrying digging and ploughing mechanisms [27]. The broader field-robot literature approaches the same physics from the opposite direction: Grimstad and From argue for minimising machine mass to protect soil structure [18], which is in direct tension with the mass needed to generate drawbar force. This tension — light enough to spare the soil, heavy enough to pull an implement through it — is the central unresolved mechanical problem for small tillage robots, and no reviewed source resolves it analytically for the sub-kilowatt class.

5.7 Multipurpose agricultural robots

Multipurpose platforms attempt to amortise capital cost across several operations. Two distinct design philosophies are visible. The first fixes several implements permanently to one chassis, each with its own actuator, and selects between them in software; this is the approach of the low-cost solar designs [27], [28] and of the sprinkler-sprayer combination of Chand *et al.* [26]. The second treats modularity as the primary requirement: Thorvald II is designed so that the same basic modules can be rebuilt into substantially different robots using hand tools, allowing one investment to serve open-field, polytunnel and greenhouse work [18]. The first philosophy is cheaper and simpler but carries the mass and cost of every implement on every task; the second is more capable but demands mechanical and software interfaces that the low-cost literature has not developed. A modular interface for smallholder-scale platforms is an identifiable gap.

5.8 Microcontroller-based agricultural robots

A large body of work builds agricultural platforms on 8-bit microcontrollers with H-bridge motor drivers, precisely because the resulting systems are inexpensive, low-power and serviceable with widely available parts [26]–[28]. Their strengths are deterministic timing for motor control, tolerance of electrically noisy environments, and a development toolchain accessible without specialist training. Their limitations are structural rather than incidental: limited program and data memory rules out on-board vision or machine learning, there is no operating system to enforce isolation between control and communication tasks, and diagnostic instrumentation is usually absent, so failures are hard to attribute after the fact. Single-board computers remove these constraints at a cost in price, power and boot-time reliability [6], [34]. The literature contains few systematic comparisons of the two choices under a stated field-robot requirement, and none that includes energy overhead as a criterion.

VI. TECHNOLOGY COMPARISON

Table 3 compares representative systems across the dimensions defined in Table 1. Only information stated in, or unambiguously implied by, the cited sources is entered; cells marked "not reported" indicate that the source does not supply the datum, and no value has been inferred. The prevalence of such cells is itself one of the findings of this review, and is analysed in Section VIII.

Table 3. Technology comparison of representative agricultural robot studies. "Not reported" denotes information absent from the cited source.

Study	Robot type	Power source	Controller / platform	Communication	Agricultural task	Autonomy level	Major contribution	Major limitation
Åstrand and Baerveldt [11], 2002	Wheeled mobile platform	Not reported	On-board vision and control computer	Not reported (autonomous)	Mechanical weed control	Autonomous	Vision-based row following combined with individual weed detection on a mobile platform	Dependent on illumination and crop-row structure; research-scale cost
Blasco *et al.* [12], 2002	Vision-directed weeding system	Not reported	Machine-vision system	Not reported	Weed control	Autonomous (task level)	Early demonstration of machine-vision-directed robotic weed control	Constrained throughput; controlled conditions
Slaughter *et al.* [10], 2008	Review of systems	Not applicable	Not applicable	Not applicable	Weed control	Autonomous (surveyed)	Defines the four enabling subsystems of autonomous weed control and reviews progress in each	Review, not an implemented platform; predates modern perception methods
Ruckelshausen *et al.* [17], 2009	Four-wheel autonomous field robot	Not reported	Multi-sensor platform with RTK-corrected satellite positioning	Not reported	Plant phenotyping and soil measurement	Autonomous	Established the reconfigurable autonomous instrument-carrier paradigm (BoniRob)	High sensor and platform cost; not aimed at implement work

Study	Robot type	Power source	Controller / platform	Communication	Agricultural task	Autonomy level	Major contribution	Major limitation
Bakker *et al.* [36], [13], 2010–2011	Purpose-designed weeding platform	Not reported	On-board control system	Not reported	Inter-row weeding	Autonomous	Systematic derivation of platform design from the weeding requirement; autonomous navigation demonstrated in sugar beet	Single crop and single operation; no energy analysis reported
Gonzalez-de-Santos *et al.* [19], 2017	Heterogeneous ground and aerial fleet	Conventional tractor-based ground units	Distributed controllers with supervisory base station	Wireless links to base station	Weed and pest control, selective spraying	Autonomous, fleet-coordinated	Demonstrated fleet-scale patch treatment as a substitute for uniform application	Very high system cost and integration burden; infrastructure dependent
Bawden *et al.* [14], 2017	Field robot with multiple end-effectors	Not reported	On-board perception and control	Not reported	Species-specific weed management	Autonomous	Per-plant selection of treatment according to weed species	Research-scale perception cost; energy demand not reported
Grimstad and From [18], 2017	Modular re-configurable tool carrier	Battery-electric	Configuration-agnostic modular control architecture	Not central to the contribution	Generic tool carriage across production systems	Autonomous and supervised	Hardware and software modularity allowing rebuild with hand tools; low ground pressure by design	Cost above smallholder reach; implement interfaces assume trained users
Utstumo *et al.* [15], 2018	In-row weeding robot	Not reported	On-board control and actuation	Not reported	In-row weed control in vegetables	Autonomous	Addressed the in-row zone inaccessible to conventional mechanical implements	Crop-specific; throughput and energy demand not reported
McAllister *et al.* [16], 2019	Team of small autonomous robots	Not reported	Distributed control	Inter-robot coordination	Weeding by coverage	Autonomous, multi-robot	Coverage allocation across a robot team	Simulation-weighted evaluation; energy and cost not central

Study	Robot type	Power source	Controller / platform	Communication	Agricultural task	Autonomy level	Major contribution	Major limitation
Ranjitha *et al.* [28], 2019	Wheeled multipurpose platform	Photovoltaic panel with battery	8-bit microcontroller with motor drivers	Short-range wireless link to hand-held application	Seed sowing, grass cutting, pesticide spraying	Tele-operated	Low-cost solar multipurpose platform commanded from a hand-held interface	Link range not characterised in crop; no energy management or MPPT reported
Chand *et al.* [26], 2021	Wheeled multi-purpose farming robot	Photovoltaic with battery	Embedded controller with computer vision and IoT connectivity	IoT connectivity for monitoring	Water sprinkling and pesticide spraying	Semi-autonomous decision making	Automated the application decision from sensed plant and soil state on a PV-powered platform	Vision performance illumination-dependent; continuous operation limited by energy budget
Pretto *et al.* [20], 2021	Integrated aerial and ground system	Battery-electric	Multi-vehicle software architecture	Inter-vehicle and ground-station links	Precision farming, monitoring and treatment	Autonomous	Adaptable aerial–ground architecture transferable across crops and sites	System complexity and cost; requires skilled operation
Ghobadpour *et al.* [24], 2023	Differential-drive agricultural mobile robot (energy study)	Photovoltaic with battery and range extender	Simulation model of powertrain and energy management	Not applicable	Generic field working cycles	Not the object of study	Optimisation-based sizing of PV, storage and range extender over realistic working cycles	Model-based; no field implementation of the complete robot reported
Poojari *et al.* [27], 2024	Solar multifunctional platform (design study)	Photovoltaic with battery	Not the object of study	Not reported	Seed sowing, digging, ploughing	Not reported	Computational structural analysis of chassis and implement mechanisms	Control, communication and energy management not addressed

VII. KEY TECHNOLOGIES USED IN SOLAR AGRICULTURAL ROBOTS

This section reviews the subsystems that recur across the designs surveyed above. Where a subsystem corresponds to a component specified in the project synopsis discussed in Section X, the correspondence is noted — but the reviewed literature establishes only that the class of component is appropriate, not that any particular implementation performs as intended. Fig. 2 shows how the subsystems relate as layers.

7.1 Photovoltaic power system

The array is characterised by its rated power at standard test conditions, its open-circuit and maximum-power-point voltages, and its temperature coefficients. For robot-scale systems the operative constraint is projected area rather than any of these, and the practical design question is therefore not how much power the array can produce at noon but how much energy it can deliver into storage across a working day [22], [24]. Small panels rated at a few watts and matched to a nominal twelve-volt bus are the standard choice in the low-cost class [27], [28]; such an array cannot sustain locomotion and implement operation simultaneously and functions as a trickle source that extends time between external charges.

7.2 Rechargeable battery system

Storage buffers the mismatch between generation and demand. Sealed lead-acid packs remain common in low-cost designs for reasons of price, robustness and tolerance of simple charge control, while lithium-iron-phosphate and lithium-ion chemistries dominate research platforms where energy and power density justify the cost and the additional management electronics [22], [25]. As noted in Section 4.3, the decisive parameters for a field robot are usable depth of discharge and peak discharge current rather than nameplate capacity, and the reviewed low-cost literature reports neither.

7.3 Voltage regulation

A field robot has at least two electrical domains with incompatible requirements: a logic domain demanding a clean, stable low-voltage rail, and an actuator domain that draws large, abrupt currents and injects switching and commutation noise onto the bus. Linear regulators are adequate and common for the logic rail at these power levels, at the cost of dissipating the difference between input and output as heat; switching regulators are more efficient and correspondingly more demanding of layout. The engineering issue emphasised in the actuator literature is decoupling: motor current transients that reach the controller supply cause resets and spurious behaviour, and the mitigation is separation of the supply paths rather than a larger regulator [34].

7.4 Microcontrollers

Eight-bit microcontrollers with hardware timers, pulse-width-modulation outputs and asynchronous serial interfaces are sufficient for command decoding and motor coordination and are the standard platform in the low-cost class [26]–[28]. Their advantages are deterministic timing, low quiescent power, immediate start-up and high electrical robustness. Their limits appear as soon as perception is required: the memory and arithmetic throughput needed for image processing are absent, so vision-guided designs move to single-board computers or add a co-processor [6], [34], [35]. Reviews of perception subsystems make clear that this boundary — not motor control — is where controller selection actually matters [6].

7.5 DC motors and motor drivers

Brushed permanent-magnet DC motors with reduction gearing dominate small agricultural platforms because they deliver high torque at low speed, are trivially controlled by voltage and direction, and are inexpensive; brushless machines with electronic commutation offer higher efficiency and better thermal behaviour at higher cost and control complexity [34]. Driver stages are conventionally H-bridges, either as integrated circuits for low-current applications or as discrete MOSFET bridges for higher current. Two constraints recur in reviews of agricultural actuation. First, integrated bridges have modest current ratings and significant conduction losses, so continuous operation near their rating produces thermal derating and eventual shutdown. Second, implement loads are not steady: engagement transients and stall conditions can demand several times running current, and a driver sized for the running case will fail in the field even though it passes bench testing [34], [35].

7.6 Radio-frequency communication

The command link determines both the working envelope and the failure modes of a tele-operated platform. Sub-gigahertz industrial-scientific-medical band modules are attractive for their propagation characteristics, low power and low cost, and are widely used in low-cost designs; Bluetooth links to a smartphone application are the other common choice [28]. The wireless agriculture literature is unambiguous that the crop canopy is a hostile propagation environment: attenuation through vegetation is substantial and depends on frequency, moisture content and growth stage, which is a principal reason low-power wide-area technologies such as LoRaWAN have become the default for agricultural telemetry [29], [30]. Those technologies trade data rate and latency for range, however, which limits their suitability for direct motion control and leaves the short-range direct-control case comparatively unstudied.

7.7 Chassis and locomotion

Skid-steer differential drive with four driven wheels is the prevailing arrangement for small field robots: it eliminates steering linkages, turns within its own footprint and distributes traction across all wheels [4], [5]. Its cost is scrubbing during turns, which consumes energy and disturbs the soil surface. Alternatives in the reviewed literature include explicit four-wheel steering, as in BoniRob [17], and the modular wheel-and-steering assemblies of Thorvald II, which allow the same components to be configured as differential drive, Ackermann steering or all-wheel steering [18]. Across designs, the governing consideration is ground pressure: reducing it protects soil structure and reduces rolling resistance, but a lighter machine can generate less drawbar force, which is the constraint that binds when an implement must be pulled through soil [18], [27].

7.8 Cutting mechanisms

Cutting implements on small platforms are typically rotating blades or discs driven directly by a dedicated motor. Three design considerations recur. The rotational inertia of the cutter produces a starting transient far above running current, which sizes the driver stage and the battery's discharge capability rather than the average power. Cutting height and ground following determine whether the implement cuts, misses or strikes soil, and are mechanical rather than control problems. Exposure of a rotating blade is the dominant hazard on such a machine, and the safety literature treats removal of the operator from that zone as a principal benefit of robotisation [2], [7] — which places a corresponding obligation on the designer to define the implement's behaviour when the command link is lost.

7.9 Digging and soil-engaging mechanisms

Soil-engaging implements transmit reaction forces into the chassis and demand traction from the wheels, coupling the implement to the locomotion subsystem in a way that cutting does not. Poojari *et al.* analyse the resulting chassis stress and deformation computationally for a small solar platform [27]. The design space is bounded on one side by the soil-protection argument for low mass [18] and on the other by the traction needed to develop drawbar force; no reviewed source provides a design method that resolves this trade-off for platforms in the sub-kilowatt class, which is why depth of work in small-robot tillage studies is generally shallow and reported qualitatively.

7.10 Remote-control and tele-operation systems

A tele-operation system comprises an operator interface, an uplink, an on-board receiver and a command interpreter. Reviewed implementations use discrete command sets — direction, speed step, implement on or off — rather than continuous control, which reduces bandwidth and simplifies decoding [28]. The literature is notably silent on three points that determine field usability: the latency budget from operator action to actuator response, the failure behaviour on link loss, and whether the operator receives any feedback beyond direct observation of the machine. Each is a tractable engineering question and each is largely unaddressed in the low-cost class.

7.11 Autonomous navigation technologies

Autonomous navigation in the reviewed platforms rests on one of two foundations, usually both. Satellite positioning with real-time kinematic correction supplies absolute position at the accuracy required for row-scale work and underpins platforms such as BoniRob and the RHEA fleet [17], [19]. Relative guidance from perception — crop-row detection, obstacle detection, visual servoing — supplies the local accuracy needed for plant-level treatment and is the subject of the largest body of methodological work [6], [10], [11], [14]. Reviews of perception subsystems indicate that sensing hardware and algorithms are increasingly capable but that their integration cost, power demand and robustness under field illumination remain the binding constraints for low-cost platforms [6], [34], [35].

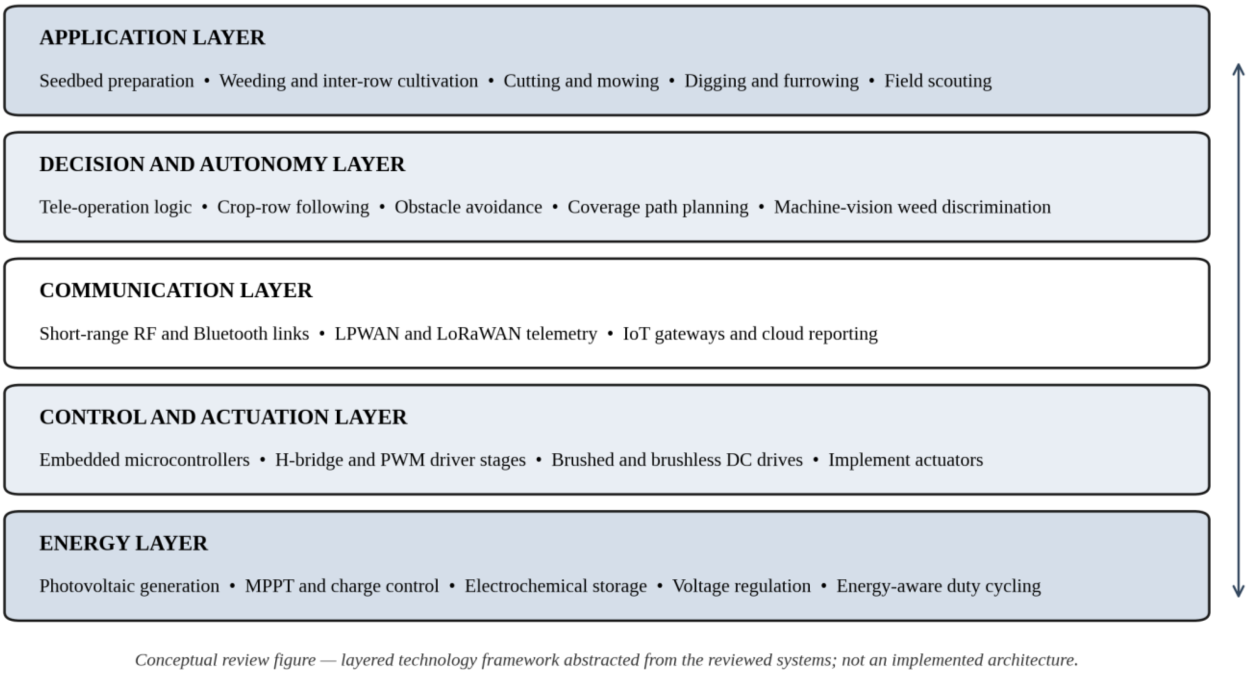

Fig. 2. Conceptual review figure: layered technology framework for solar-powered agricultural robotics, abstracted from the reviewed systems. The figure organises subsystem relationships and does not depict an implemented architecture.

Table 4. Comparison of control and communication technologies reported in the reviewed literature.

Technology	Typical role	Reported range behaviour	Power demand	Suitability for small field robots	Limitation identified in the literature
Sub-GHz ISM radio modules	Direct tele-operation command link	Favourable propagation relative to 2.4 GHz; in-crop range rarely measured	Low	High — low cost, low power, adequate latency for discrete commands	Vegetation attenuation is frequency- and moisture-dependent and is not characterised in the reviewed robot papers [29], [30]
Bluetooth to smartphone application	Operator interface and command link	Short; degrades rapidly with obstruction	Low	Moderate — convenient interface, restricted working envelope	Operator must remain close to the machine [28]
Wi-Fi	Higher-rate telemetry and video	Short to moderate; infrastructure dependent	Moderate to high	Low to moderate — useful near a farmstead, not across a field	Power and coverage cost disproportionate for command-only use [29]
LPWAN / LoRaWAN	Telemetry, monitoring, status reporting	Long range at low data rate	Very low	High for monitoring, low for motion control	Latency and duty-cycle constraints make it unsuitable for direct actuator control [29], [30]
Satellite positioning with RTK correction	Absolute localisation for autonomy	Coverage-wide, accuracy dependent on correction service	Moderate	Low at smallholder cost levels	Requires correction infrastructure and raises system cost substantially [17], [19]

Technology	Typical role	Reported range behaviour	Power demand	Suitability for small field robots	Limitation identified in the literature
On-board vision	Relative guidance and plant-level discrimination	Not applicable	Moderate to high	Low to moderate — constrained by controller class and energy budget	Illumination sensitivity and integration cost remain binding constraints [6], [26]

VIII. CRITICAL ANALYSIS OF EXISTING SYSTEMS

Read together rather than individually, the reviewed literature displays a consistent asymmetry: the subsystems that are intellectually interesting are documented in depth, and the subsystems that determine whether a machine works on a farm are documented thinly or not at all. The following analysis is organised around that asymmetry.

8.1 Energy and solar charging

Energy is the least consistently reported dimension in the entire reviewed set. Table 3 records "not reported" for the power source of most autonomous research platforms, and this is not an artefact of selective reading: papers whose contribution is perception or navigation routinely omit the energy budget altogether. Conversely, the low-cost solar papers state array and battery ratings but not the energy accounting that would make those ratings meaningful — average and peak load, expected insolation, achievable working period, depth of discharge. Ghobadpour *et al.* are the clear exception, showing that sizing must proceed from the working cycle rather than the peak load [24]. The practical consequence of the general omission is that the reviewed body of work does not permit comparison of solar robots on energy performance, and cannot be used to predict whether a proposed configuration will complete a given task.

8.2 Battery capacity, payload and motor power

Three quantities are mutually constrained in a small field robot: implement power, battery mass and traction. Increasing implement capability raises peak current, which requires a larger pack or a higher-rate chemistry; a larger pack adds mass, which raises rolling resistance and traction demand and therefore consumption; and additional mass increases ground pressure, which the soil-protection argument seeks to minimise [18]. The reviewed low-cost literature treats these as independent design choices rather than as a coupled system. Reviews of agricultural actuation note the same discontinuity from the actuator side, observing that implement actuation and its power demands have received far less attention than navigation [34], [35].

8.3 Communication range and radio interference

For tele-operated designs the command link defines the usable working area, yet no reviewed robot paper reports a measured link budget within a standing crop. The wireless agriculture literature makes clear why this matters: propagation through vegetation is strongly attenuating and varies with frequency, moisture and growth stage, so a range figure obtained across open ground overstates in-field performance, possibly by a large factor [29], [30]. Interference is a second unexamined issue, since the shared ISM bands are increasingly occupied by farm telemetry. Most seriously, the reviewed papers seldom state the platform's behaviour on link loss; a machine with an engaged rotating cutter and an undefined fail state is a hazard, and the safety framing in the broader literature makes this omission difficult to defend [2], [7].

8.4 Navigation, autonomy and terrain adaptability

The autonomy literature is technically strong but economically remote. Positioning at row-scale accuracy depends on correction infrastructure [17], [19]; perception-based guidance depends on computation and on illumination conditions [6], [11], [14]. Neither dependency is compatible with smallholder cost levels, which is why the affordable end of the field remains tele-operated despite three decades of autonomy research. Terrain adaptability is a related gap: the reviewed platforms are generally evaluated on prepared, relatively uniform ground, whereas the fields for which low-cost robots are intended are frequently irregular, residue-covered and bounded by bunds. Thorvald II is the notable case of a platform whose geometry can be reconfigured to the environment [18], but reconfiguration is a design-time rather than run-time capability.

8.5 Implement integration and modularity

Two incompatible approaches to multifunctionality coexist in the literature without being compared. Fixed multi-implement platforms carry every mechanism at all times, paying in mass, cost and complexity for functions not in use [27], [28]. Modular tool carriers exchange implements, but the only well-documented modular architecture is aimed at research and commercial users rather than smallholders [18]. No reviewed source specifies a mechanical and electrical implement interface — mounting, drive coupling, power and control connection — appropriate to a low-cost platform, and its absence is a concrete, addressable gap.

8.6 Cost, maintenance and scalability

Pedersen *et al.* established two decades ago that economic feasibility, not technical capability, governs whether an agricultural robot is adopted [8]. The reviewed engineering literature has largely not taken up this challenge: cost is mentioned as a motivation far more often than it is quantified, and maintenance, spare-part availability, expected service life and repairability are almost entirely absent. This is a serious omission for the smallholder case, where a machine that cannot be repaired locally is effectively disposable. Sparrow and Howard argue that the distributional and social consequences of agricultural automation deserve equal weight with its technical performance [7], and the absence of cost and serviceability data makes those consequences impossible to assess.

8.7 Safety and environmental robustness

Field robots operate in shared, uncontrolled space and carry hazardous implements, yet explicit safety analysis is rare outside the review literature [2], [7]. Environmental robustness is similarly under-reported: ingress protection against dust and water, thermal behaviour of driver stages under sustained load in direct sun, vibration tolerance of connectors and fasteners, and resistance to ultraviolet degradation of enclosures all determine whether a prototype survives a season, and none is systematically reported in the reviewed set.

IX. RESEARCH GAPS

The gaps stated below are drawn from the analysis in Section VIII and each is traceable to specific evidence in the reviewed sources. Where a gap rests on the *absence* of reporting rather than on a positive finding, this is stated as such: absence of evidence in a thematic review is a weaker claim than a demonstrated negative, and the distinction is preserved deliberately. Fig. 3 groups the gaps into three clusters and Table 5 sets out the supporting evidence.

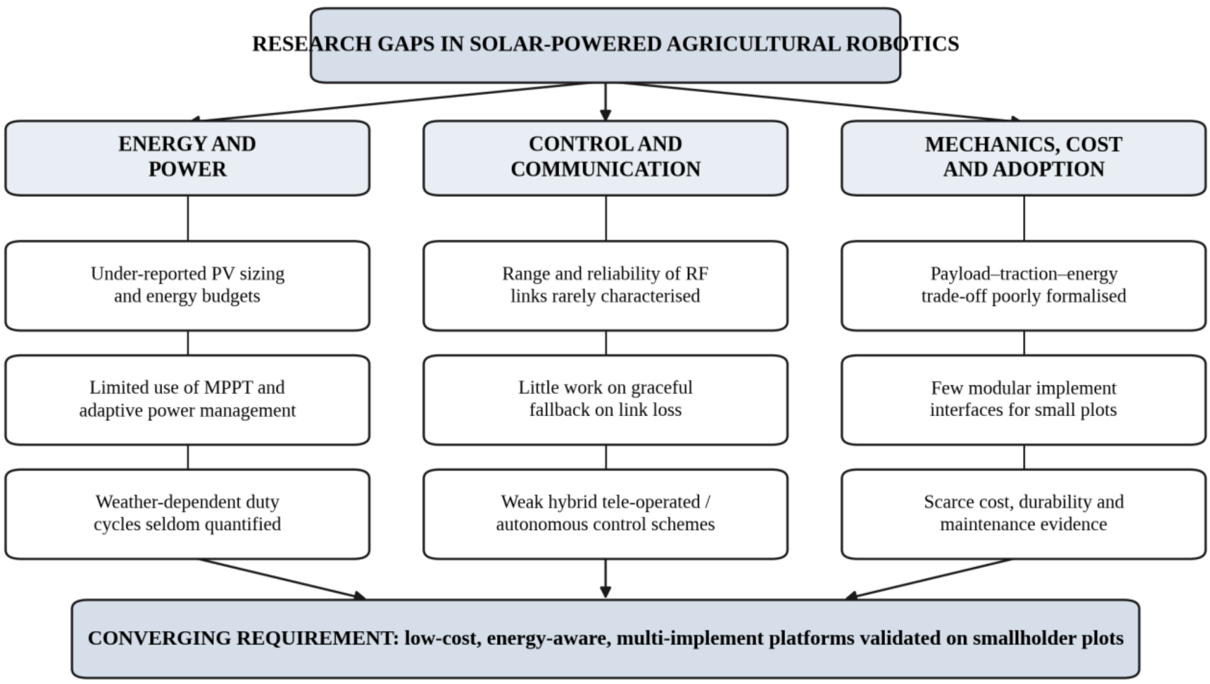

Fig. 3. Conceptual review figure: research-gap framework derived from the critical analysis in Section VIII, grouped into energy, control and communication, and mechanical–economic clusters.

Table 5. Summary of research gaps, supporting evidence and consequences.

No.	Research gap	Basis in the reviewed literature	Consequence
G1	Reproducible energy budgets for solar field robots	Energy accounting is absent from most reviewed platform papers; only [24] derives sizing from a working cycle	Solar robots cannot be compared on energy performance and achievable working periods cannot be predicted
G2	Adaptive power management and MPPT in low-cost designs	Sophisticated energy management appears only in research-grade work [24], [25]; low-cost designs report simple charge control [27], [28]	Available generation is under-used and the working period varies with weather in ways the system neither measures nor reports
G3	Characterisation of short-range command links in standing crop	No reviewed robot paper reports in-crop link measurements; the wireless literature documents substantial vegetation attenuation [29], [30]	Stated control ranges are not transferable to field conditions, and working envelopes are effectively unknown
G4	Defined fail-safe behaviour on loss of command link	Failure behaviour is not specified in the reviewed tele-operated designs, against a literature that treats operator safety as a principal benefit of robotisation [2], [7]	A machine with an engaged implement may have an undefined state, which is a direct safety hazard
G5	Formalisation of the payload–traction–energy trade-off	Low mass is argued for soil protection [18] while drawbar force requires mass [27]; no reviewed source resolves the tension for sub-kilowatt platforms	Tillage-capable small robots are designed by iteration rather than analysis, and work depth remains shallow and qualitatively reported
G6	Low-cost modular implement interfaces	Modularity is well developed only for research and commercial platforms [18]; low-cost designs fix all implements permanently [27], [28]	Capital cost cannot be amortised across operations, and every task carries the mass of every implement
G7	Hybrid tele-operated and autonomous operating modes	The literature is polarised between full autonomy [13], [17], [19] and pure tele-operation [28], with little treatment of graduated transfer of control	Affordable platforms cannot incrementally adopt autonomy as its cost falls
G8	Cost, durability and maintenance evidence	Economic feasibility was identified as decisive in [8]; the reviewed engineering literature rarely quantifies cost and almost never reports serviceability	Adoption prospects for smallholders cannot be assessed, and social impact analysis is obstructed [7]
G9	Terrain adaptability and environmental robustness	Evaluation is generally on prepared uniform ground; ingress, thermal and vibration performance are not systematically reported	Prototype results do not predict seasonal survival on irregular smallholder plots
G10	Integration of sensing and intelligent navigation at low cost	Perception is capable but integration cost, power and illumination robustness remain binding [6], [34], [35]	Plant-level precision, the principal agronomic benefit of robotics, remains inaccessible to the platforms that most need it

X. PROPOSED SYSTEM CONCEPT BASED ON THE REVIEW

This section describes a proposed solar-powered agricultural robot documented in a separate project synopsis. Everything stated here is a *design proposal*: the configuration has not been experimentally validated, no measured performance data exist, and nothing in this section should be read as a demonstrated improvement over any reviewed system. The purpose of including it is to locate the proposal within the research landscape mapped above and to identify which of the gaps in Table 5 the architecture engages, in principle, and which it does not.

10.1 Proposed architecture

The proposed concept is a compact four-wheeled platform carrying two independently actuated implements — a cutter and a digger — commanded over a short-range radio link and supplied from an on-board photovoltaic panel with battery storage. The synopsis specifies a 12 V, 5 W solar panel; a 12 V, 1.2 Ah rechargeable battery; a 7805 series regulator for the logic rail; an ATmega328 microcontroller as the command interpreter and motor coordinator; a 433 MHz transmitter and receiver pair for the command link; two L293D driver integrated circuits, one for the four locomotion motors and one for the cutting and digging motors; and development in the Arduino integrated development environment with circuit design in Proteus. Fig. 4 shows the conceptual architecture in the layered terms established in Section VII.

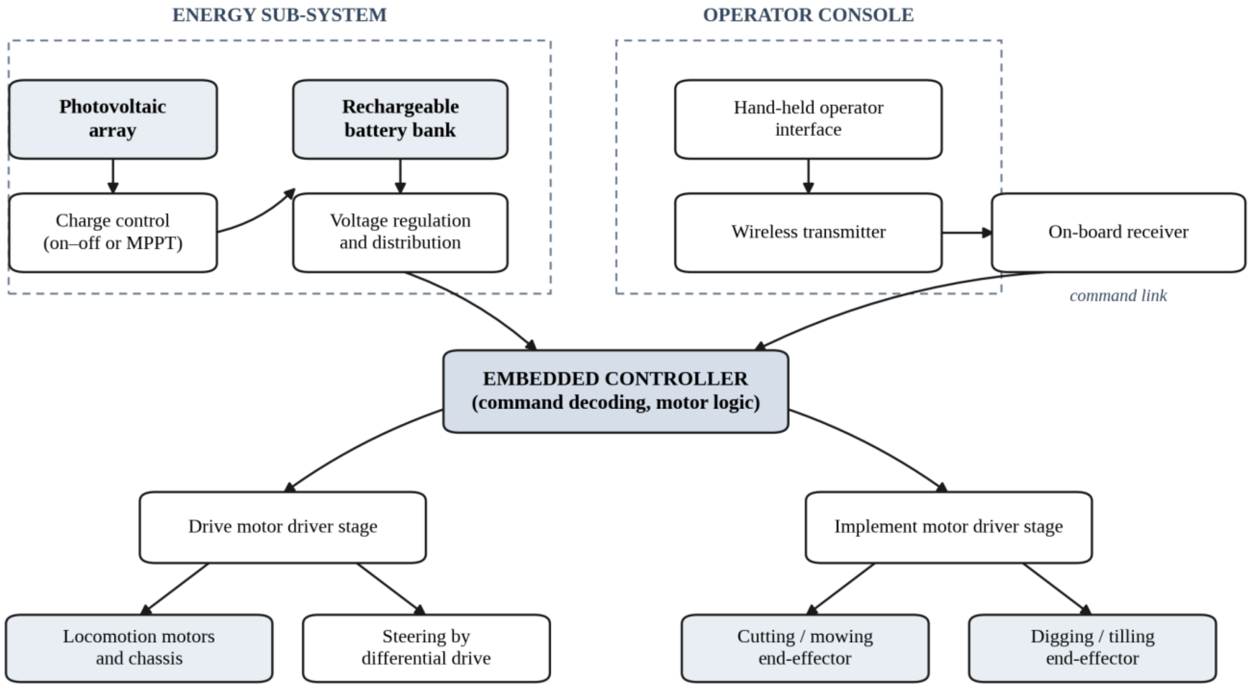

Fig. 4. Conceptual architecture of the proposed solar-powered agricultural robot, drawn at the block level from the project synopsis. This is a proposed design, not an experimentally validated system.

10.2 Relation of each element to the reviewed literature

The photovoltaic-plus-battery topology is consistent with the configuration reported across the reviewed solar platforms, in which the array replenishes storage over an interval longer than the interval of use rather than supplying the load directly [24], [26]. It should be stated plainly that a 5 W array and a 1.2 Ah battery constitute a very small energy system relative to the demands of soil engagement identified in Section 7.9; on the evidence of [24] the achievable working period would be determined by the duty cycle of the digging implement and would require measurement rather than calculation from nameplate ratings. This is a matter for experimental work, and the review supports no claim about it either way.

Differential drive on four wheels is the prevailing arrangement in the reviewed platforms and is well supported as a choice for small field robots [4], [5], [17]. Dedicating a separate driver stage to the implements, rather than sharing one with locomotion, is consistent with the actuation literature's observation that implement engagement transients dominate the electrical load and should not be allowed to disturb the locomotion supply [34], [35]. Separating the logic rail through its own regulator addresses the decoupling problem discussed in Section 7.3, although a linear regulator dissipates the surplus as heat and its thermal behaviour in an enclosure under direct sun is exactly the kind of environmental-robustness question that gap G9 identifies as under-reported.

The 8-bit microcontroller is appropriate to the stated function — decoding discrete commands and sequencing motor drivers — and matches the class used in comparable published designs [26]–[28]. It also fixes a ceiling: on-board perception is not available on this platform, so the concept sits firmly at the tele-operated end of the autonomy spectrum and cannot incrementally adopt the vision-based capabilities reviewed in Section 7.11 without a change of controller class. The 433 MHz link occupies the sub-gigahertz band whose propagation advantages are recognised in the wireless agriculture literature [29], [30]; equally, gap G3 applies directly, and any range figure for this configuration would need to be established by measurement inside a standing crop rather than assumed or quoted from open-ground testing.

10.3 Which gaps the concept engages

Table 6 sets the proposed concept against typical reported practice in the reviewed systems and records, for each aspect, whether a gap from Table 5 is engaged, partially engaged or left open. The honest summary is that the architecture engages the cost and multi-implement gaps (G6, G8) at the level of design intent, that it inherits rather than resolves the energy and communication gaps (G1–G3, G5), and that it creates an obligation with respect to G4, since a platform with a powered cutter and a radio link must define its behaviour when that link fails.

Table 6. Proposed concept versus typical reported practice in the reviewed systems.

Aspect	Typical practice in the reviewed literature	Proposed concept (from project synopsis)	Gap engaged or left open
Energy supply	PV with battery buffering; energy budget seldom reported [24], [26]–[28]	12 V, 5 W panel with 12 V, 1.2 Ah battery	G1 left open — a working-cycle energy budget would need to be measured, not assumed
Power management	Simple charge control in low-cost designs; MPPT and optimisation only in research-grade work [24], [25]	Series regulator for the logic rail; no MPPT specified	G2 left open — the concept follows low-cost practice rather than improving on it
Control platform	8-bit microcontrollers in low-cost designs; single-board computers where vision is required [6], [26]–[28]	ATmega328 with Arduino toolchain	Appropriate to the stated function; caps future autonomy (G10 left open)
Command link	Short-range radio or Bluetooth; in-crop range not characterised [28]–[30]	433 MHz transmitter and receiver pair	G3 left open; measurement in crop required before any range claim
Failure behaviour	Rarely specified in tele-operated designs [2], [7]	Not specified in the synopsis	G4 engaged as an obligation — a defined fail-safe state is required for a powered cutter
Locomotion	Four-wheel differential drive prevalent [4], [5], [17]	Four DC motors on a wheeled chassis, differentially steered	Consistent with established practice; G9 left open
Implements	Either all implements fixed permanently, or research-grade modularity [18], [27], [28]	Dedicated cutting motor and dedicated digging motor on separate driver stage	G6 partially engaged — two functions on one platform, but interfaces are not modular
Soil engagement	Payload–traction–energy trade-off unresolved for small platforms [18], [27]	Digging implement on a light chassis	G5 left open and directly relevant to feasibility
Cost orientation	Cost cited as motivation, rarely quantified [8]	Low-cost commodity components throughout	G8 engaged in intent; quantification and serviceability assessment still required

XI. DISCUSSION

The reviewed literature establishes several results firmly. Plant-level sensing and treatment are technically achievable: vision-guided weeding, species-specific treatment and in-row operation have all been demonstrated on working platforms [11], [14], [15]. Lightweight electric platforms are a coherent alternative to tractor-scale mechanisation, with soil protection as an explicit design driver rather than a side effect [18], [33]. Modularity is a productive architectural principle, shown by the ability to rebuild one set of modules into substantially different machines [18]. Fleet and multi-robot operation is feasible and shifts the economics away from single large machines [16], [19], [20]. And renewable supply for agricultural machinery has moved from proposition to engineering discipline, with formal treatment of source sizing and energy management now available [22]–[25].

What existing systems do well, they do at a price. The autonomous research platforms achieve repeatable, plant-scale precision but depend on positioning infrastructure, substantial computation and skilled support; their cost places them beyond the farms that constitute the majority of the world's holdings [9]. The low-cost tele-operated designs are affordable and serviceable but supply no precision benefit beyond removing the operator from the hazard zone, and they are reported in a way that does not permit assessment of what they can actually achieve in a working session. Between these two populations there is very little: few designs occupy the middle ground of modest cost with partial, incrementally extensible autonomy, and the literature offers no design methodology for that region.

Solar-powered robots can contribute most where the fuel supply chain is the binding constraint and the operations are light and intermittent — precisely the profile of smallholder cultivation. The contribution is conditional, however, on treating energy as a first-class design variable rather than as a nameplate specification. The single most transferable finding in this review is that sizing must proceed from the working cycle [24]: an array and a pack are adequate or inadequate only relative to a stated task, duty cycle and insolation, and a design that does not state these cannot be evaluated. Adopting working-cycle reporting as a norm would do more for comparability in this literature than any individual technical advance.

For small farms specifically, low-cost multipurpose platforms are attractive because they amortise capital across operations and because a machine assembled from commodity components can be repaired locally — a property the reviewed literature almost never discusses but which determines whether a machine survives its second season. Realising that benefit requires modular implement interfaces suitable for low-cost construction, which is gap G6, and it requires the cost and serviceability evidence identified as absent in gap G8. Sparrow and Howard's argument that distributional consequences deserve weight comparable to technical performance is directly relevant here [7]: a technology whose economics are undocumented cannot be assessed for its social effects either.

The technological improvements the literature most clearly indicates are therefore not exotic. They are: energy accounting reported as a working-cycle budget; maximum-power-point tracking and simple load-shedding logic brought down into the low-cost class; measured characterisation of command links inside crop canopies; explicitly defined fail-safe states for powered implements; an analytical treatment of the payload–traction–energy trade-off for sub-kilowatt platforms; and a documented, inexpensive implement interface. Each is incremental in isolation; together they would move the low-cost end of this field from demonstration to engineering.

XII. FUTURE RESEARCH DIRECTIONS

The directions below follow from the gaps in Table 5. They are ordered from those requiring least additional cost to those requiring most, on the reasoning that affordability is the binding constraint for the platforms this review is most concerned with.

- *Energy-aware operation and adaptive power management.* Bringing maximum-power-point tracking, state-of-charge estimation and load-shedding logic into low-cost designs, and reporting achievable working periods against a stated duty cycle, would address G1 and G2 at modest component cost [24], [25].
- *Measured wireless characterisation.* Link-budget measurement inside standing crops across growth stages, for both sub-gigahertz and 2.4 GHz links, would replace assumed ranges with evidence and would inform the choice between direct control and gateway-mediated architectures [29], [30].
- *Defined fail-safe behaviour and safety design.* Specification and testing of platform behaviour on link loss, implement stall and low battery state — including automatic implement disengagement — is a low-cost, high-value contribution [2], [7].

- *Modular implement attachments.* Design and publication of an inexpensive mechanical and electrical implement interface, with documented mounting, drive coupling and control connection, would let one platform serve several operations without carrying all of them [18].
- *Improved motor control.* Closed-loop speed and current control, soft-start for high-inertia cutters and stall detection would reduce peak demand on the pack and driver stages and extend component life [34], [35].
- *Obstacle detection and low-cost sensing.* Ultrasonic and infrared proximity sensing, wheel odometry and inertial sensing are cheap enough for this class and would support graduated autonomy without a change of controller architecture [6], [34].
- *Battery technology and storage management.* Comparative field evaluation of lithium-iron-phosphate and lithium-ion packs against lead-acid on cost per delivered kilowatt-hour, cycle life under partial-state-of-charge operation and peak current capability [22], [25].
- *Energy-aware path planning.* Coverage planning that accounts for the energy cost of turning, of scrubbing in skid-steer manoeuvres and of implement engagement, rather than path length alone [16], [24].
- *Satellite positioning and RTK correction.* Assessment of what row-scale accuracy costs in money, power and complexity for smallholder platforms, and whether shared or network-provided correction alters that calculus [17], [19].
- *Soil and crop sensing with IoT connectivity.* Integration of soil moisture, temperature and canopy sensing with low-power wide-area reporting, so that a working platform also serves as a data-collection instrument [26], [29], [30].
- *Computer vision and machine learning for crop and weed discrimination.* Adaptation of demonstrated discrimination methods to the computational and energy budgets of low-cost platforms, which is the central obstacle rather than algorithmic capability [6], [10], [14].
- *Hybrid tele-operated and autonomous control.* Architectures permitting graduated transfer of authority between operator and machine, so that autonomy can be adopted incrementally rather than as an all-or-nothing investment [7], [31], [32].
- *Remote monitoring and cloud or mobile integration.* Status, energy and task reporting to a mobile interface, which is inexpensive to implement and directly addresses the diagnostic opacity noted in Section 5.8 [29], [30].

XIII. CONCLUSION

Agricultural robotics has moved from proposition to engineering discipline over three decades, and the reviewed literature now supports the claim that plant-level sensing and treatment, lightweight electric platforms, modular tool carriage and coordinated multi-robot operation are all technically achievable [4], [5], [11], [14]–[20]. Solar supply has followed the same trajectory: photovoltaic generation for agricultural machinery is no longer a demonstration topic but a design problem with formal methods available for source sizing and energy management [22]–[25].

The review nonetheless identifies a persistent division in the field. Autonomous research platforms deliver precision at a cost that excludes the majority of the world's farms, which are small holdings [9], while the low-cost tele-operated designs intended for those farms are reported too thinly to be evaluated. Energy budgets are seldom stated in reproducible form; maximum-power-point tracking and adaptive power management appear almost exclusively in research-grade work; the behaviour of short-range command links inside crop canopies has not been measured in any reviewed robot paper; failure behaviour on link loss is generally unspecified even where a powered cutter is fitted; the payload–traction–energy trade-off that governs small tillage platforms has not been formalised; low-cost modular implement interfaces do not exist in the published record; and cost, durability and maintenance evidence — identified as decisive for adoption twenty years ago [8] — remains largely absent.

Against these gaps, the proposed solar-powered agricultural robot concept examined in Section X is best described as a design that engages the affordability and multi-function questions while inheriting the field's unresolved energy and communication problems. Its topology is consistent with published practice: photovoltaic generation buffered by storage, four-wheel differential drive, a separate driver stage for implements, and an 8-bit controller matched to discrete command interpretation [4], [5], [26]–[28], [34]. Its value, if it is realised, will lie in the measurements it produces rather than in the architecture itself — a working-cycle energy budget, an in-crop link characterisation, a defined fail-safe state and a costed bill of materials would each address a documented gap. No performance claim is made for the concept in this paper, and none is supported by the reviewed literature.

The broader potential of the field is substantial but conditional. Solar-powered, multi-implement platforms are a plausible answer to the specific combination of constraints that smallholder agriculture presents: small plots, unreliable fuel and grid supply, scarce labour and thin capital. Realising that potential depends less on further advances in perception or autonomy, which are already ahead of what affordable platforms can carry, than on a change in reporting and design practice at the low-cost end — energy accounting from the working cycle, measured communication performance, explicit safety states, and honest quantification of cost and serviceability. Those are the contributions this review identifies as most needed and most achievable.

REFERENCES

[1] A. Bechar and C. Vigneault, "Agricultural robots for field operations: Concepts and components," *Biosystems Engineering*, vol. 149, pp. 94–111, 2016.

[2] A. Bechar and C. Vigneault, "Agricultural robots for field operations. Part 2: Operations and systems," *Biosystems Engineering*, vol. 153, pp. 110–128, 2017.

[3] R. R. Shamshiri, C. Weltzien, I. A. Hameed, I. J. Yule, T. E. Grift, S. K. Balasundram, L. Pitonakova, D. Ahmad, and G. Chowdhary, "Research and development in agricultural robotics: A perspective of digital farming," *International Journal of Agricultural and Biological Engineering*, vol. 11, no. 4, pp. 1–14, 2018.

[4] L. F. P. Oliveira, A. P. Moreira, and M. F. Silva, "Advances in agriculture robotics: A state-of-the-art review and challenges ahead," *Robotics*, vol. 10, no. 2, art. 52, 2021.

[5] S. Fountas, N. Mylonas, I. Malounas, E. Rodias, C. Hellmann Santos, and E. Pekkeriet, "Agricultural robotics for field operations," *Sensors*, vol. 20, no. 9, art. 2672, 2020.

[6] A. Thakur, S. Venu, and M. Gurusamy, "An extensive review on agricultural robots with a focus on their perception systems," *Computers and Electronics in Agriculture*, vol. 212, art. 108146, 2023.

[7] R. Sparrow and M. Howard, "Robots in agriculture: prospects, impacts, ethics, and policy," *Precision Agriculture*, vol. 22, no. 3, pp. 818–833, 2021.

[8] S. M. Pedersen, S. Fountas, H. Have, and B. S. Blackmore, "Agricultural robots — system analysis and economic feasibility," *Precision Agriculture*, vol. 7, no. 4, pp. 295–308, 2006.

[9] S. K. Lowder, J. Skoet, and T. Raney, "The number, size, and distribution of farms, smallholder farms, and family farms worldwide," *World Development*, vol. 87, pp. 16–29, 2016.

[10] D. C. Slaughter, D. K. Giles, and D. Downey, "Autonomous robotic weed control systems: A review," *Computers and Electronics in Agriculture*, vol. 61, no. 1, pp. 63–78, 2008.

[11] B. Åstrand and A.-J. Baerveldt, "An agricultural mobile robot with vision-based perception for mechanical weed control," *Autonomous Robots*, vol. 13, no. 1, pp. 21–35, 2002.

[12] J. Blasco, N. Aleixos, J. Roger, G. Rabatel, and E. Moltó, "AE—Automation and emerging technologies: Robotic weed control using machine vision," *Biosystems Engineering*, vol. 83, no. 2, pp. 149–157, 2002.

[13] T. Bakker, K. van Asselt, J. Bontsema, J. Müller, and G. van Straten, "Autonomous navigation using a robot platform in a sugar beet field," *Biosystems Engineering*, vol. 109, no. 4, pp. 357–368, 2011.

[14] O. Bawden, J. Kulk, R. Russell, C. McCool, A. English, F. Dayoub, C. Lehnert, and T. Perez, "Robot for weed species plant-specific management," *Journal of Field Robotics*, vol. 34, no. 6, pp. 1179–1199, 2017.

[15] T. Utstumo *et al.*, "Robotic in-row weed control in vegetables," *Computers and Electronics in Agriculture*, vol. 154, pp. 36–45, 2018.

[16] W. McAllister, D. Osipychev, A. Davis, and G. Chowdhary, "Agbots: Weeding a field with a team of autonomous robots," *Computers and Electronics in Agriculture*, vol. 163, art. 104827, 2019.

[17] A. Ruckelshausen *et al.*, "BoniRob — an autonomous field robot platform for individual plant phenotyping," in *Precision Agriculture '09, Proc. 7th European Conference on Precision Agriculture*, Wageningen, The Netherlands, 2009, pp. 841–847.

[18] L. Grimstad and P. J. From, "The Thorvald II agricultural robotic system," *Robotics*, vol. 6, no. 4, art. 24, 2017.

[19] P. Gonzalez-de-Santos *et al.*, "Fleets of robots for environmentally-safe pest control in agriculture," *Precision Agriculture*, vol. 18, pp. 574–614, 2017.

[20] A. Pretto *et al.*, "Building an aerial–ground robotics system for precision farming: An adaptable solution," *IEEE Robotics & Automation Magazine*, vol. 28, no. 3, pp. 29–49, 2021.

[21] C. W. Bac, E. J. van Henten, J. Hemming, and Y. Edan, "Harvesting robots for high-value crops: State-of-the-art review and challenges ahead," *Journal of Field Robotics*, vol. 31, no. 6, pp. 888–911, 2014.

[22] S. Gorjian *et al.*, "The advent of modern solar-powered electric agricultural machinery: A solution for sustainable farm operations," *Journal of Cleaner Production*, vol. 292, art. 126030, 2021.

[23] A. Ghobadpour, L. Boulon, H. Mousazadeh, A. S. Malvajerdi, and S. Rafiee, "State of the art of autonomous agricultural off-road vehicles driven by renewable energy systems," *Energy Procedia*, vol. 162, pp. 4–13, 2019.

[24] A. Ghobadpour, A. Cardenas, G. Monsalve, and H. Mousazadeh, "Optimal design of energy sources for a photovoltaic/fuel cell extended-range agricultural mobile robot," *Robotics*, vol. 12, no. 1, art. 13, 2023.

[25] A. Ghobadpour, G. Monsalve, A. Cardenas, and H. Mousazadeh, "Off-road electric vehicles and autonomous robots in agricultural sector: Trends, challenges, and opportunities," *Vehicles*, vol. 4, no. 3, pp. 843–864, 2022.

[26] A. A. Chand, K. A. Prasad, E. Mar, S. Dakai, K. A. Mamun, F. R. Islam, U. Mehta, and N. M. Kumar, "Design and analysis of photovoltaic powered battery-operated computer vision-based multi-purpose smart farming robot," *Agronomy*, vol. 11, no. 3, art. 530, 2021.

[27] M. Poojari *et al.*, "Computational modelling for the manufacturing of solar-powered multifunctional agricultural robot," *International Journal on Interactive Design and Manufacturing (IJIDeM)*, vol. 18, pp. 5725–5736, 2024.

[28] B. Ranjitha, M. N. Nikhitha, K. Aruna, Afreen, and B. T. V. Murthy, "Solar powered autonomous multipurpose agricultural robot using Bluetooth/Android app," in *Proc. 3rd International Conference on Electronics, Communication and Aerospace Technology (ICECA)*, IEEE, 2019, pp. 872–877.

[29] B. Citoni, F. Fioranelli, M. A. Imran, and Q. H. Abbasi, "Internet of Things and LoRaWAN-enabled future smart farming," *IEEE Internet of Things Magazine*, vol. 2, no. 4, pp. 14–19, 2019.

[30] S. Sadowski and P. Spachos, "Wireless technologies for smart agricultural monitoring using Internet of Things devices with energy harvesting capabilities," *Computers and Electronics in Agriculture*, vol. 172, art. 105338, 2020.

[31] A. Roshanianfard, N. Noguchi, H. Okamoto, and K. Ishii, "A review of autonomous agricultural vehicles (the experience of Hokkaido University)," *Journal of Terramechanics*, vol. 91, pp. 155–183, 2020.

[32] V. Rondelli, B. Franceschetti, and D. Mengoli, "A review of current and historical research contributions to the development of ground autonomous vehicles for agriculture," *Sustainability*, vol. 14, no. 15, art. 9221, 2022.

[33] M. Gonzalez-de-Soto, L. Emmi, C. Benavides, I. Garcia, and P. Gonzalez-de-Santos, "Reducing air pollution with hybrid-powered robotic tractors for precision agriculture," *Biosystems Engineering*, vol. 143, pp. 79–94, 2016.

[34] D. Xie *et al.*, "Actuators and sensors for application in agricultural robots: A review," *Machines*, vol. 10, no. 10, art. 913, 2022.

[35] C. Cheng *et al.*, "Recent advancements in agriculture robots: Benefits and challenges," *Machines*, vol. 11, no. 1, art. 48, 2023.

[36] T. Bakker, K. van Asselt, J. Bontsema, J. Müller, and G. van Straten, "Systematic design of an autonomous platform for robotic weeding," *Journal of Terramechanics*, vol. 47, pp. 63–73, 2010.