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A Systematic Review of Low-Cost, High-Impact, Frugal Robotics for Precision Agriculture in Sub- Sahara Africa

Ezirim Kelechi ThankGod[1*], Sani Abubakar Muhammed[2], Aniugo Victor Onyekachi[3], Nwaokolo Ikechukwu Frank[4], Obi Obichukwu Immanuel[5], Okoronkwo Iheanyi Chinedu[6] & Aminu Momoh[7]

[1,2,3,4,5,6]Mechatronics Engineering Department; Federal University of Technology, Owerri, Imo State, Nigeria

[7]Transmission Company of Nigeria, Akangba Sub-Region, Lagos State, Nigeria

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ABSTRACT **Review Article**

Agriculture employs a staggering 60% of Sub-Saharan Africa's (SSA) total workforce, yet overall productivity remains questionably low due to labor shortages, input waste, and climate variability (FAO, 2023). Frugal robotics visibly characterized by low-cost, are locally serviceable robots designed majorly for resource-constrained farms unarguably offers a pathway to scale precision agriculture (PA) in SSA. This systematic review examines the state-of-the-art in low-cost robotic systems for weeding, planting, spraying, monitoring, and post-harvest in SSA. Analysis of 47 studies and 23 deployed prototypes from 2017-2025 was made with findings showing that while technical performance is improving, adoption is limited by power access, network connectivity, maintenance, and business models. High-impact applications cluster around autonomous weeders, UAV scouting, and sensor-based irrigation. Hence the proposal of a frugal robotics framework: modular hardware, solar power, offline AI, and community ownership. Future research must prioritize co-design with smallholders, local manufacturing, and pay-as-you-go models to cover 2-hectare farms.

Keywords: Frugal Robotics, Precision Agriculture, Sub-Saharan Africa, Smallholder Farming, Low-Cost Automation, AgriTech.

**Corresponding author: Ezirim Kelechi ThankGod*

Mechatronics Engineering Department; Federal University of Technology, Owerri, Imo State, Nigeria

Introduction

Sub-Saharan Africa, undeniably is presently facing challenges ranging from feeding rapidly increasing population as high as over 1 billion people by 2030; dealing with an aging farming workforce who engages obsolete and outdated farming equipment and as well as exponentially rising input costs (World Bank, 2022).

AGRA, (2021) observed that the average farm size is usually less than (<2) two hectares, making traditional tractors and large precision agricultural (PA) equipment economically unviable.

Frugal innovation best described as "doing more with less" has been proposed as a solution (Radjou & Prabhu, 2015). Therefore, the application of robotics, means engaging systems that cost less than USD5000 (<$5000), with solar-powered, repairable with local parts, and operable offline. This is quite a departure from the high-end agribots in the US/EU hence frugal robots must tolerate dust, rain, poor GSM network, limited technical support and such other conditions associated with developing countries (Daum et al., 2022).

Admittedly, recent advances in open-source hardware, edge AI, and low-cost sensors make this feasible. Projects like

FarmBot, AgBot, and Turtle have been successfully adapted for SSA (Rivera et al., 2020). Unfortunately, literature is yet fragmented across engineering, development, and social science.

This review seeks to address vital concerns: What low-cost robotic platforms exist for SSA agriculture? What impact do they have? What technical and socio-economic gaps remain? Attempt is made to focus on robots that costs less than (<$10,000) USD10,000 while targeting farms of sizes less than (<10)10 hectares.

Literature Review

Precision Agriculture (PA) in SSA

Precision Agriculture uses data and automation to optimize inputs. In Sub- Sahara Africa, Precision Agriculture has particularly focused more on soil mapping, mobile advisory, and drip irrigation (Shepherd et al., 2015).This has exposed the fact that robotics adoption vigorously lags behind due to operational cost and required infrastructure capacity.

Frugal Innovation and Robotics

Frugal robotics on the other hand emphasizes more on affordability, robustness, and local value chains (Weyrauch & Herstatt, 2017). The major design principles taken into consideration include: modularity, use of COTS parts, and minimal energy draw (Bhatti, 2012).

Robotic Applications in Agriculture

Globally, the major sophisticated robots applied in agriculture often referred to as agribots cover five (5) main domains: 1. Weeding, 2. Planting/Seeding, 3. Spraying, 4. Monitoring/UAV, and 5. Harvesting (Duckett et al., 2018). Regrettably, in Sub- Sahara Africa, harvesting robots are rare due to crop diversity and cost.

Sub-Sahara Africa Context

Constraints: Visible challenges include: intermittent power, <3G connectivity, dusty conditions, and varied terrain (Adenle, 2020). Opportunities: Obvious opportunities existing in the region include: high labor cost at peak season, youth interest in tech, and donor funding for climate-smart agriculture.

Methodology

This systematic review followed PRISMA principles engaging Search Strategy; Inclusion and Exclusion Concept; Data Extraction and Analytic process of classification.

Results

Categories of Frugal Robots in SSA

We identified four clusters: Category; Examples; Cost Range; and Key Function

1. **Category: Autonomous Weeders**
   Example: SolarWeeder, Zenvus Bot.
   Cost: $800 -$3500.
   Key Function: Mechanical weeding, no herbicide.
2. **Category: UAVs & Ground Scouts**
   Example: Aerobotics and DroneDeploy clones.
   Cost: $500 - $4000.
   Key Function: Crop health mapping, pest detection.
3. **Category: Planting/Irrigation Bots**
   Example: SunCulture, Irrigation Scheduler Bot.
   Cost: $300 - $2500.
   Key Function: Precision planting, drip control.
4. **Category: Post-Harvest Robots**
   Example: Hello Tractor attachments, Sorter bots.
   Cost: $1000 - $8000.
   Key Function: Grading, shelling, transport.

Technical Characteristics

Rivera et al., (2020) observe that while 80% of the robots use solar + battery, 65% use edge AI on Raspberry Pi/Jetson Nano and the common sensors adopted include RGB camera, soilmoisture, GPS but a staggering 70% operate offline with weekly data sync.

Reported Impact

Weeding robots reduce labor by 40-60% and herbicide use by 30% (Akinyemi et al., 2021). UAV scouting is seen to increase yield by 12-18% via early disease detection (Steyn et al., 2020). Unfortunately, just less than 20% (<20%) of pilot robots scale beyond 50 farmers.

Barriers

Common limitations with the adoption of robots in Sub-Sahara Africa Precision Agriculture include:

1. **Technical:** Dust ingress, battery degradation, poor GPS under multiple tree canopy and coverage
2. **Economic:** High upfront cost, no financing, unclear return-on-investment (ROI) for 1-ha farms.
3. **Social:** Low digital literacy, trust issues, gender access gap (Daum et al., 2022).

Deductions

1. **Cost-Performance Tradeoff:** Robots are usually expensive. Those that cost less than $2000 work well but have limited autonomy. Those that cost from $5000 and above are more sophisticated and do perform better but are relatively unaffordable by many.
2. **Energy is the Bottleneck:** Solar should bring solace but cloudy weeks halt operations unplanned.
3. **Service Model greater than Product:** Robots-as-a-service outperforms direct sales in Sub -Saharan Africa.

4. **Local Manufacturing Matters:** Imported robots fail in performance expectations due to lack of spares parts as Locally assembled units often have thrice higher uptime.

Discussion

Frugal robotics can reliably and reasonably bridge the Precision Agriculture gap in Sub -Saharan Africa but "copy-paste" from Europe will definitely fail. The regional (SSA) farms need swarms of cheap, simple robots, not one that cost as much as $100,000 machine (Duckett et al., 2018).

Three obvious insights emerged from the review:

First, impact is highest in labor peaks like during weeding and spraying. Second, data is more valuable than the robot as scouting UAVs that send WhatsApp alerts are adopted faster than autonomous tractors (Shepherd et al., 2015). Third, ecosystem is key since without local dealers, financing, and training, robots rust in sheds (AGRA, 2021).

This aligns with frugal innovation theory but extends it to accommodate technical frugality which must be paired with business model frugality inorder to achieve maximum result.

Gaps and Future Targets

1. **All-Terrain Locomotion**: Engage Low-cost wheels and tracks for muddy Sub -Sahara African fields during rains.
2. **Offline AI:** On-device models for weed ID and disease that don't need cloud.
3. **Interoperability:** Open standards to enable a weeder to share data with an irrigation bot.
4. **Gender-Responsive Design:** Lighter robots operable by women who do 60% of weeding.
5. **E-waste & Circularity:** Design for repair and battery recycling.
6. **Evidence Base:** RCTs measuring yield, income, and labor impact, not just tech demos.

Recommendations

The following recommendations are made for various stakeholders to wit:

For Developers:

1. **Co-design with farmers:** Test in real 1-2 ha fields for 2 seasons before scaling.
2. **Modularize:** Sell base chassis + task attachments to reduce cost.
3. **Use local parts:** Motors, solar panels, and frames sourced in-country.

For governments and NGOs:

1. **Subsidies and Pay As You Go (PAYG):** Vouchers or lease-to-own for small holders.
2. **Training Hubs:** County-level repair and operator training.

For researchers:

1. **Benchmarks:** Standard test plots for weeding accuracy and energy use.
2. **Business Model Research:** Study cooperatives and service providers, not just tech.

Conclusion

Admittedly, Low-cost, high-impact robotics can make precision agriculture viable for Sub-Saharan Africa's small holders. The technology do exist, but anticipated success depends much more on frugal design, appropriate business models, and local ecosystems. The next agricultural revolution should intentionally and strategically shift from prototypes to durable, serviceable, farmer-owned robotic fleets. Otherwise, Sub -Saharan Africa risks being left behind in the global robust agri-robotics revolution already making waves across the globe.

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