Robotics, IoT, and AI in the Automation of Agricultural Industry: A Review

[1]Akshay Krishnan
krishnanakshay19@outlook.com

[2]Shashank Swarna
swarnashashank@gmail.com

[3]Balasubramanya H. S
baluhs.md@gmail.com

[1,2,3]*Department of Mechanical Engineering*
Ramaiah Institute of Technology
Bengaluru, India

***Abstract*—This paper presents a review on various agricultural practices and aspects that can be or currently are automated, using robotics, IoT and Artificial Intelligence (AI) more prolifically. Alongside, the current and future perspectives are dealt with, covering major technology innovations focused around smart farming, precision agriculture, vertical farming, modern greenhouse practices, autonomous and robotic workforce, drones, and the 'connected farm.' Post Covid-19, automation of agricultural industry has become all the more relevant to the new norm set due to labour migration and shortage.**

Keywords—Robotics, AgBots, Agriculture, Automation, IoT, AI

I. Introduction

Agricultural industry has been one of the most integral parts for the economic and social development of any country. With the current population of more than 7 billion, the world is just scraping through its food needs. Moreover, with an exponential growth in the population in the next 25-30 years, our current supply of food may not be sufficient. In fact, it is predicted that we need our food supply to increase by at least 70% for the world to sustain [1]. Unlike other sectors, the agricultural industry is yet to have its 'boom' in the current millennium.

Thomas Malthus propounded in his famous 'theory of population growth' [2], that the population increase is observed in geometric progression compared to agricultural produce increasing in arithmetic progression. Ehrlich and Ehrlich [3] from Stanford University and Jared Diamond [4] concur that there is a likelihood of starvation and deprivation due to finite resources but led by increased consumerism. Therefore, the farm produce needs to improve multi-fold and productively with finite resources of land, labour, material and capital becoming scarce day by day.

Philip Kotler [5] in his paper, 'The consumer in the age of coronavirus' explains that, with the prediction of UN that population will likely to grow to 9.8 billion by 2050, top soil getting eroded, arable land getting shrunk, oceans partly becoming dead zones with depleting marine species, it looks seemingly impossible to feed the starving mouths at the current production rate. Thanks to human ingenuity, another revolution is in the offing to circumvent this possible scenario.

In the foreseeable future, automatization of agriculture industry using artificial intelligence (AI), IoT and expert system albeit minimal human judgement, error and interference are gaining recognition. To do so, we need to implement robots and autonomous systems which are key aspects of automation. Needless to say, there have been sightings of robots here and there in the nooks and corners of the industry but nothing significant to change the traditional methods of farming. In this review paper, there will be some proposals that are low hanging fruits, that can be implemented cost effectively within a shorter time span while other proposals are purely theoretical at this point but requiring coordinated approach with complex technology to improve the yield multi-fold.

II. Smart Farming

Smart farming (Fig. 1) is a recent phenomenon gaining recognition in the agricultural industry wherein advances in technology including big data, machine learning, AI, cloud computing and the internet of things (IoT) are integrated into the various stages of manual/mechanized/automated operations involved in the entire crop production cycle.

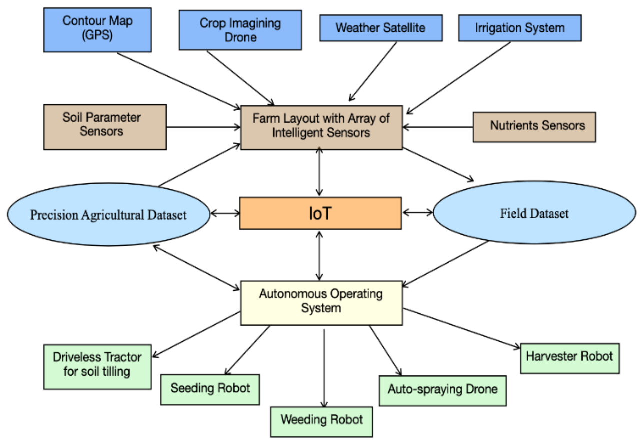

Fig. 1. Schematic of 'smart' farm configuration.

It is one of the most efficient and the best bet for a better future in terms of growing food crops (e.g. wheat, rice and millet) and cash crops (e.g. corn, cotton and spices). The advantage of it is also the integration of modern and latest technologies with the existing farming techniques allowing farmers to have a comfortable and smooth transition. Overall, farm automation technology encompasses water management, optimum utilization of seeds, energy conservation and environmental footprint.

III. Precision Agriculture

In order to promote the development of automation in the agricultural field, environmental monitoring system aids in gathering fast, accurate and constant measurements required in precision agriculture [6]. Precision agriculture comprises of using GPS, soil scanning and IoT technology to precisely measure the variations within the field. In grid soil sampling [7], the first step is to divide the field into a grid of small and equal cells. The field grid is scanned through a satellite and signals are sent to a dish antenna fitted on a tractor which helps in taking soil samples mechanically from each cell and

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tested in a modern soil testing laboratory including physical and chemical characteristics. Colour grams are generated through variable-rate fertilizer application technique [8], for the entire field and stored electronically, which in turn are used to automatically apply fertilizers at variable rates only where they are needed. This brings uniformity and balancing of soil fertility, thus optimizing crop yields. Such techniques of selective usage can greatly increase the effectiveness of pesticides and herbicides.

Historic data are maintained electronically or physically in the form of soil health cards. Importantly, site-specific differences within arable fields are identified, evaluated and timely preventive/corrective actions are taken. For example, considering the moisture content of the soil and atmosphere using humidity sensors and weather forecast through geo-spatial systems, the quantity and flow of water for irrigation can also be precisely controlled specific to a domain/cell, for optimum utilization and conservation of water.

Thus, precision agriculture provides accurate information and data through the entire crop cycle dynamically and in real-time through technologies, enabling farmers to maximize yields by controlling every variable of crop farming such as humidity levels, losses due to pest ingress, soil parameters and environment conditions.

IV. Vertical Farming

Vertical farming (Fig. 2) addresses the shortage of land resource and can be implemented in urban areas. Recent advances in crop technology like hydroponics, aquaponics and aeroponics do not require soil. Aquaponics uses fish to provide nutrients whereas hydroponics uses formulated solutions. In aeroponics, nutrient mist is sprayed on the roots of the plants hanging in air. Popular crops are, microgreens and herbs (e.g. arugula, radicchio & basil), "baby greens" (e.g. spinach, kale & lettuce) and sprouts (e.g. broccoli, soya bean & wheat).

Fig. 2. Vertical farm [10].

Temperature, humidity, light and CO_2 levels in atmosphere are all measured, monitored and controlled 24/7 using sensor technology and nutrients are periodically injected and fine-tuned based on stages of growth integrated through AI and IoT to get the optimum results. This sets a new paradigm in urban farming and is a relatively recent phenomenon in food production requiring minimal supervision but generating higher yield [9]. As per B. Kurt *et al* [10], growth of crops in indoor farming with a controlled environment can be improved through genetic engineering.

Terraces and balconies of existing skyscrapers could be effectively put to use for indoor vertical farming. Environment is impacted minimally by reduced emission of greenhouse gases since the distance travelled in the supply chain is also drastically cut down [10]. To get the maximum exposure to sunlight, rotating base is designed with every vertical stack enclosure. It is possible to adapt vertical farming totally indoors or underground in basements, but calls for a controlled environment requiring artificial 'grow lights' as against to natural sunlight. Further, vertical farming could become a very cost-effective solution for the urban population due to reduced water consumption, energy usage and lower logistic and storage cost compared to traditional farms. On the contrary, vertical farming may be difficult to cultivate broad-acre crops like wheat, rice or millet for mass consumption.

V. Modern Greenhouses

Greenhouse farming has been traditionally operating on a small scale primarily in nurseries prepared by tissue culture and botanical gardens for floriculture. In recent times, greenhouse farming is being used for fruits and vegetables as well. Greenhouses are classified according to the type of construction, material, shape and ventilation [11]. Structure could be wooden or pipe framed and covering material could be glass or UV stabilized polythene/polyethylene material. Sawtooth, ridge, multi-span and Quonset shaped greenhouses are common.

Fig. 3. Typical view of modern greenhouse [12].

Natural ventilated greenhouses use shade nets to prevent access to pests and bacteria. But if natural breeze is allowed, crops under this type of farming are still prone to be affected by airborne diseases. Apropos poly-pad based ones are fully enclosed (Fig. 3) for climate control and the internal environment is fully and artificially managed.

IoT is used to perform a host of functions to tailor the environment for crop health and growth [13], by:

- Rationing water using drip tubes/porous pads/sprinklers through micro-irrigation techniques.
- Diagnosing and maintaining soil pH, moisture content and nutrient requirements through intelligent sensors.
- Monitoring and controlling light intensity 24/7 through LED lights, meeting plant-specific temperature and humidity requirements through automated climate control systems.
- Energy conservation through effective use of solar panels.

Closed greenhouse is very effective in controlling crop pests and diseases. However, it requires professional knowledge and skills in regulating the environment. One of the primary advantages is that the yield can be shielded from the vagaries of climate conditions. As a result, erstwhile season dependent farm produce is now grown throughout the year thereby creating the demand, scaling up the production and catering for local preferences. Practically all types of root based (e.g. yams, onions & potatoes), plant based (e.g. pulses, tomatoes & oranges), shrub type (e.g. lemons, colour capsicums & berries) and creeper type (e.g. grapes, cucumber & gourds) can be cultivated. Organic farm products and exotic types are also grown and sold at a premium to the health-conscious consumers. Needless to say, the modern greenhouse farming is bringing crop cultivation to doorstep customer delivery within the proximity of urban hubs.

VI. Autonomous And Robotic Workforce

The technology used for automating crop production cycle is at the core of farm automation, which in turn becomes the first building block of 'smart' farming. Extensive research shows that easier and mundane tasks are getting automated at a faster pace through innovations in the development of drones, autonomous tractors, robotic seeding and harvesting, and drip/sprinkler irrigation.

On the application front, agricultural robots (AgBots) are used at various stages of crop cycle from planting, watering, to harvesting and sorting. Ultimately, integrating all these AgBots through a reliable array of intelligent sensors inbuilt with IoT will become the cornerstone for the success of farm automation. Pivotal to a truly 'smart' farm is the ability of all the devices, equipment and system to seamlessly communicate in real-time and dynamically with each other and at the same time maintaining appropriate interface with the human commands while not hindering to operate autonomously.

A. From Bullock Driven to Autonomous Tractor

Traditionally small farmers used bullocks as a source of physical energy to plough the fields. The ploughman walks behind the bullocks in the scorching sun. On an average, a pair of bullock ploughs 0.12 to 0.80 hectare in a day [14], involving a lot of drudgery. The beginning of mechanization of agriculture was made by the use of improved hand tools and bullock-drawn implements. For example, attaching a triangular metal plate to the body of the ubiquitous plough helped in making furrows and ridges to sow seeds and harvest crops (e.g. ground nuts & potatoes) but the output still remained abysmally low.

Contraptions and attachments for motorized tractors were developed to suit the type of crop to be cultivated. For example, a long tube with multiple holes at the bottom with a seed bowl, as an ancillary equipment to the tractor ensured that multiple rows of seeds are planted in the field at a fraction of time and effort compared to manual method. This earliest innovation is scaled up to become autonomous with its advanced functions. Initially, efforts will be required to customize the usage by mapping the field and its envelope, and programming the optimum path based on the contours of the terrain. With lead through and teach-in programming knowledge, farmers will be able to perform mundane tasks with limited autonomy.

According to S. M. A. Ekram *et al* [15], advancement in machine vision and cameras, GPS for navigation, obstacle detection through radar and avoidance, laser guidance and perimeter control, IoT for remote control and monitoring will convert the tractors into truly autonomous vehicles and safely perform intelligent functions as well. Further in the foreseeable future, companies like John Deere and Case-IH are actively working to take the next leap of technology that would use 'big data' in real time. For example, the weather forecast through satellite interface could be used to perform tasks such as sowing and harvesting under best suited conditions devoid of human judgement and autonomously.

B. Manual Sowing to Automated Aerial Seed Distribution

Covering large open fields for manual sowing of seeds is time consuming and labour intensive. Typical seeding machines scatter the seeds and can cover large areas faster than manual method, but wasteful when seeds fall beyond the optimal location. Sowing robot developed by V. Yedave, *et al* [16], is the simplest version that performs multiple tasks of putting the seeds in rows of required depth, spaced equally, covering the seeds and compacting the soil. However, the uneven terrain and soil conditions bring additional variability that needs to be addressed.

Geo-mapping the terrain with sensors for soil parameters takes a lot of the manual judgement out of the seeding process. This led to the development of self-propelled precision seeding robots designed to control the terrain and location specific depth of seeding and distance between seed plantations. Thus, the probability of a good and cost-effective harvest gets vastly enhanced right from planting stage.

Using pneumatic pistols, sealed capsules containing seed pods with fertilizer and nutrients are directly fired into the ground using drones [17]. Looking ahead, IoT-enabled system could be envisioned that makes multiple autonomous precision seeding drones programmed to precisely plant an entire field. The farmer can view and monitor the complete seeding process remotely through digital networking.

C. Flood Irrigation to Drip Feeding

Moving away from the conventional flood irrigation system, surface drip irrigation (SDI) or integrated network of sprinklers (INS) are already popular that allow farmers to vary the quantity and flow of water to the crops which could be seen in middle east as well, where deserts are being converted into green zones.

In the 'smart farm' context, SDI/INS irrigation system rely on an array of sensors spread in a grid pattern across the field to continuously monitor soil, environment and nutrient parameters. IoT is used for data collection and analysis to take autonomous decisions for conserving water by monitoring and rationing the water at the right time, for the right quantity and in the right location for healthy plant growth [18]. Farmer intervenes only in adverse conditions, otherwise allowing the system to operate autonomously.

D. Manual Weeding to Autospraying for Pest Control

Weeding process uses human judgement and requires intelligent system of higher order and complexity for a robot to perform the same. Similarly, pests on the move need to be dynamically monitored for remedial measures. Therefore, both operations are best suited for autonomous robots.

Researchers, A. Ruckelshausen, *et al* [19], used 'Bonirob' platform to develop a robot which at the prototype stage, offers interesting and advanced features wherein the vehicle can autonomously navigate the length and breadth of the vast terrain of cultivating land using video camera mounted onboard and interfacing with LiDAR and satellite GPS. In machine learning concept, a training set is created consisting of several images of crops and types of weeds. Every image of the crop and weed is marked with typical characteristics that differentiate the two and are collated into a data base. In operation, the robot scans the field, and the images are continually processed to identify the differentiating characteristics. Figure 4 typically shows how the length and width characteristics of leaves that can be used to differentiate between Striata and Tetralepis type of plants. Similarly, the data can be collected for the crop and weed and compared with the stored information thereby identifying the weeds before plucking them off.

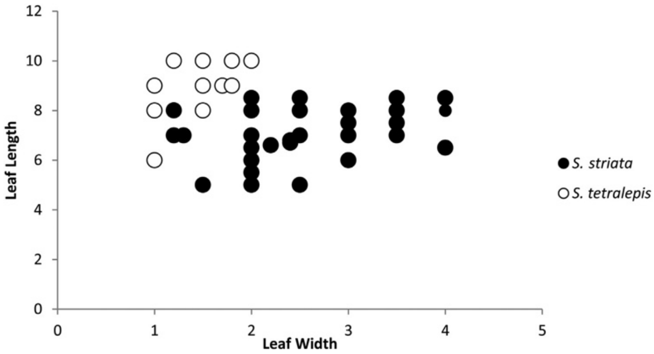

Fig. 4. Dimension of a leaf as a differentiating characteristic [20].

In future, artificial intelligence could be built through an expert system that updates the database through experiential learning, thus becoming a perception pipeline. This domain knowledge getting continually expanded forms the basis to perform the weeding operations with error rate diminishing over a time horizon. Extending the concept, a similar system can be used to identify pests and additionally selectively apply the insecticides using sprayers as end-effector.

Another interesting possibility propounded by K. HannahJoy. *et al* [21], is the use of markers like fluorescent dye coated on seeds which is an edible compound absorbed by the plant roots. As the plant grows, the dye spreads on the leaf. The leaf glows when it is exposed to a specific wavelength of light, enabling the machine vision system of the robot to recognize the crop. This principle of light differentiation is used by the robot in operation using onboard video cameras to identify the weed from the crop before removing them from the soil. Whereas on the other hand, in the process of uniquely identifying the crops through colour dying, the possibility of pests getting unduly attracted to the plant needs to be investigated.

Fig. 5. Auto-spraying drone [23].

Drones used for aerial crop spraying comprise of onboard microcontroller, a GPS and a digital map of the farm field which is uploaded to control the speed and direction of the spray gun [22]. Intelligent sensors, microwave radar and motion controllers navigate the drone to follow the trajectory both in terms of right altitude and location and at the same time compensating for factors such as wind speed, topography and geography. Advantages of this system are increased efficiency and reduced wastage of insecticides.

Recent attack of locusts has caused heavy damage to the crops. Swarms of AgBots, deployed in predetermined positions forming a grid across the field, can continuously monitor both inland and aerial invasion of pests [24]. Crops in specific location requiring special attention are identified by these AgBots. The information is communicated wirelessly through IoT so that a specific drone (Fig. 5) can provide timely individualized treatment such as spraying measured dosage of insecticide, fertilizers and nutrients to any part of the field. Thereby any menace/malady can be effectively localized/curbed/prevented from becoming widespread.

E. Manual Picking to Automated Harvesting

Tacit knowledge plays an important role in harvesting. Maturing of the crop, limited window of available time, delicate handling of picking without causing damage, separating and sorting, and inclement weather conditions all add up to the complexity of issues faced by the farmers.

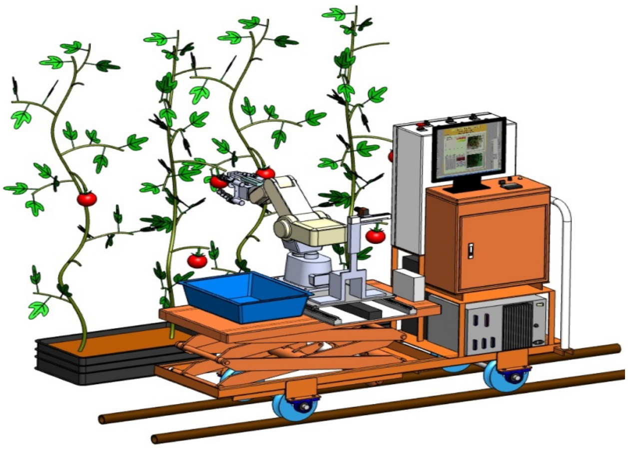

Fig. 6. Robot picking tomato [25].

N. Kondo, *et al* [26], have observed that picking and separating cluster crops from stems (e.g. cherry tomatoes & berries), require higher level of expertise compared to a large sized fruit or vegetable. A binocular stereo vision technique is used to get 3D contrast images of crop clusters & computer vision algorithms developed to arrive at readiness of the crop for harvesting based on their colour, shape and location. The feedback loop is completed by instructing a self-propelled robot to perform the harvesting. Force and tactile sensors are used along with a suitable end effector (Fig. 6) to delicately grip the tomato to prevent bruises, nick marks or damages.

With this experiment, the researchers claim a success rate of 70%. It becomes all the more challenging when a vegetable or fruit (e.g. French beans & green grapes) has a colour spectrum that is near about similar to other parts of the crop. Again, picking fruits and vegetables like lemon that grow in shrubs and lay partly/fully hidden require further investigation. The day is not far off when AgBots shall scan every individual plant across the field and pick the crop as soon as it is ripe.

F. Helicopter Viewing to Drone Imaging

Frequent aerial surveys of the property are done using helicopters or aircrafts mounted with cameras to get still pictures. But this remains cost prohibitive. Nowadays, standard photographic imaging, to infrared, ultraviolet and hyperspectral imaging is made possible offsetting the requirements to conduct surveys in daylight. 3D videos are made possible to be recorded with cameras having night vision features. With increased image resolution, granular details of the field can be viewed with clarity.

The 'big data' is digitally processed to give meaningful outputs to the farmers regarding soil quality, environment conditions, water distribution and absorption pattern and crop health thereby facilitating farmers to take appropriate decisions regarding land and crop management. It is thus observed, that advances in image capturing and high-end processing has assisted every stage of the agriculture process.

VII. Discussions

Throughout this paper, advances in technologies have rapidly started to overtly and covertly invade the humble farming. Remote sensors, satellites, LiDAR and UAVs can gather information 24/7 over an entire field. The amount of data generated is overwhelming, requiring high-end controllers and system to draw meaningful actionable decisions. The backbone of automation is the IoT that manages and acts as an interface with microcontrollers, sensors, cameras, AgBots and drones all interconnected to each other, exchanging data, and communicating in ways that transforms into farm automation.

Ongoing research suggests, efforts are on towards detailed work and motion study of various processes involved in farming in order to segregate tasks that are repetitive and standardized, thereby becoming ideal candidates for robotics and automation. Though the starting point has been to reduce undue reliance on manual labour, extensive application of autonomous robotics into farming also improves crop yield in terms of quality and quantity, efficiency and effectiveness multi-fold.

Computer, IoT and AI form the common thread for automating majority of the operations towards digital agriculture. Remote sensors are used as inputs to enable algorithms to interpret a field's environment and machine learning is used to process these inputs. Over time, the data collected leads to improved pipeline, which in turn facilitates to fine tune the algorithm and process the information for better prediction of possibilities in terms of outcome. Thereby, AI is used to improve the accuracy of decision making, in various aspects of the crop production cycle.

Taking a cue from the advancements in materials science, the basic structure and skin of drones and Agbots could be made of sheets of carbon nanotubes so that the drone conserves energy by being lighter in weight and the hollow honeycomb structure could be used to fill insecticides or nutrients thus providing uniform distribution of the load across the framework as well [27]. Added advantage is the ability of the material to withstand all weather conditions.

It is evident that AgBots spread across the field facilitate monitoring every plant from sapling to fruition. Autonomous vehicles on ground help negotiate tough terrains and provide mobility to AgBots to perform tasks right from seeding to harvesting. Drones also find their utility to primarily do visual checks and spray insecticides, fertilizers and nutrients. Capsule firing to precise locations extensively under trials for reforestation is gaining importance in agriculture as well. However, initial seed money to be invested is very high. As of now, drones have to frequently return to bases for recharging. Table. I, below summarises the technological developments required for various key functions of a 'smart' farm.

TABLE I. Typical Processes & Application Aspects in 'Smart' Farming

Function	Technological Development
Smart sensing, monitoring and construction:	
Soil temperature, humidity, CO2 & atmospheric moisture.	Infrared, ultrasound and laser sensors, force & tactile sensors, sensor field array, Nanotubes.
Smart planning & functioning: Mechanization, Robotics & UAVs	
Crop production cycle-Seeding, weeding, to harvest.	Autonomous tractors, sowing robot, Seed scattering drone, weeding robot, Harvesting robot, crop marking, swarm of AgBOTs.
Precision agriculture: smart control:	
Soil characteristics and field mapping	Grid soil sampling, colour gram & variable-rate fertilizer application.
Navigation & perimeter control	Laser guidance, LiDAR, Video camera, Geo-spatial system, contour mapping, topography, GPS & satellite imaging.
Imaging of crop, field terrain and for pests and insects	Binocular stereo vision system, standard photographic imaging, infrared, ultraviolet, hyperspectral imaging, 3D video cameras with night vision.
Automated climate control	'Grow lights', plant-specific temperature & humidity control.
Connected farming: Smart analysis & management:	
Crop health to maximise yield	Aerial crop spraying drones, dosage of Fertilizers, insecticides & pesticides.
Water conservation	Micro irrigation system integrated with drip tubes/porous pads/sprinklers, water flow, quantity, distribution & absorption pattern.
Energy conservation	Array of wind farms & solar panels system.
Data gathering, storage and Interface management	IoT, lead-through, teach-in programming, computer vision algorithms, microcontrollers, computers and tablets.
Big Data in the cloud:	
Weather/climate/yield & satellite data	ML, cloud computing, expert system & AI.

Unlike the generations gone by, wherein the farmers managed a large contingency of labourers, the farmers of this millennium will need to hone up their skills towards repair, maintenance and upkeep of complex systems. They also need to develop expertise towards managing robots and autonomous systems. Along with becoming computer savvy to debug robot programs they need to analyse and evaluate big data, cloud computing and planning farm operations.

VII. Conclusion

The extent of autonomy the farming process can achieve depends upon the degree of mechanization and automation adapted. This paper has primarily focused on crops related to agriculture of what seems to be the tip of the iceberg. There could be a resurgence of collective farming in its new avatar as a 'connected farm', for augmenting resources such as drones, autonomous vehicles and AgBots. Evidently, the way forward to achieve a guaranteed increase in food production, is towards implementation of robotics, IoT and AI in the automation of agricultural industry.

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