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Transforming seed spices crops cultivation in India: Tradition to technology

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Abstract
Seed spices are a vital component of India's spice industry, accounting for a substantial share of the country's total spice production. However, traditional seed spice cultivation methods are often labour-intensive, inefficient, and hindered by low productivity. This study explores the transformative potential of advanced technologies in enhancing seed spice crop productivity. We examine various stages of cultivation, from seedbed preparation to harvesting, highlighting the challenges faced by conventional farming practices and the solutions offered by modern agricultural techniques. The adoption of autonomous systems, robotics, precision agriculture, and sustainable practices is discussed as key drivers of change in revolutionizing seed spice cultivation. By leveraging these technologies, India's seed spice sector can significantly improve efficiency, quality, and sustainability, ensuring long-term viability and competitiveness in the global market.

Keywords: Seed spices crops, automation, driverless systems, precession, robotics

Introduction
Seed spices are crops with seed as the primary economic part, utilized in the whole or value-added form to enhance the flavor, aroma, and pungency of the food. Besides their culinary, they are widely utilized for carminative and preservation reasons in the pharmaceutical and other industries. India, with its diverse agro-climatic conditions, is a leading producer of more than 20 different seed spices. (Sarada, C. K., Giridhar and Hariprasada Rao 2011) [90]. Coriander, Cumin, dill seeds, fenugreek, and fennel are the major seed spices cultivated in the country. Different states are known for different spices, although seed spices are predominantly grown in Rajasthan and Gujarat, which contribute more than 80 percent (Singh and Solanki 2015) [97]. India stands as the global leading producer and exporter of spices, producing 7.07 MT from an area of 3.52 Mha in 2015-16. Seed spices play a critical part in the Indian spice economy, accounting for 50.31% of the area and 21.30% of total spice production (Malhotra and Vashishtha 2017) [68]. In India, chillies, cumin, coriander, garlic, and fenugreek are the most extensively cultivated spices, representing 23.05%, 22.79%, 17.48%, 8.39%, and 6.42% of the total area share, respectively. Additionally, these spices account for 21.88%, 7.25%, 8.06%, 23.07%, and 3.56% of the total spices production. Spices significantly contribute to India's export earnings.
In 2015-16, India exported 8.43 lakh tonnes of spices worth 2.633 million USD, representing approximately 12.21% of domestic production. Spice exports are highly concentrated, among 22 spices cultivated commercially in the country, 10 accounts for about 90% of overall export earnings. Over the past three decades, there has been a remarkable transformation in both spice production and export dynamics (Pareek *et al.* 2023) [80].
India exports just 15% of its annual spice production, yet this meets 50-60% of global demand. This highlights the need to significantly enhance the productivity of seed spice crops (Lagnelöv *et al.* 2023) [63]. The promptness of farm activities is seen to be more important in getting optimal yields from various crops, which is made feasible by farm mechanization. Thus, mechanization has been identified as a major factor in increasing agricultural productivity worldwide. The mechanization level of horticultural crops (Figure 1), which include, fruit, medicinal,

ornamental, spice, and seed spices crops, in various agriculture operations, i.e., seedbed preparation, sowing, weed and pest control was 60-70%, 30-40% and 40-50%. Whereas the level of mechanization in harvesting was less than 1%. There is a low level of mechanization in seed spice crops for different agricultural operations, especially in the case of harvesting (Zhang *et al.* 2024) [121].

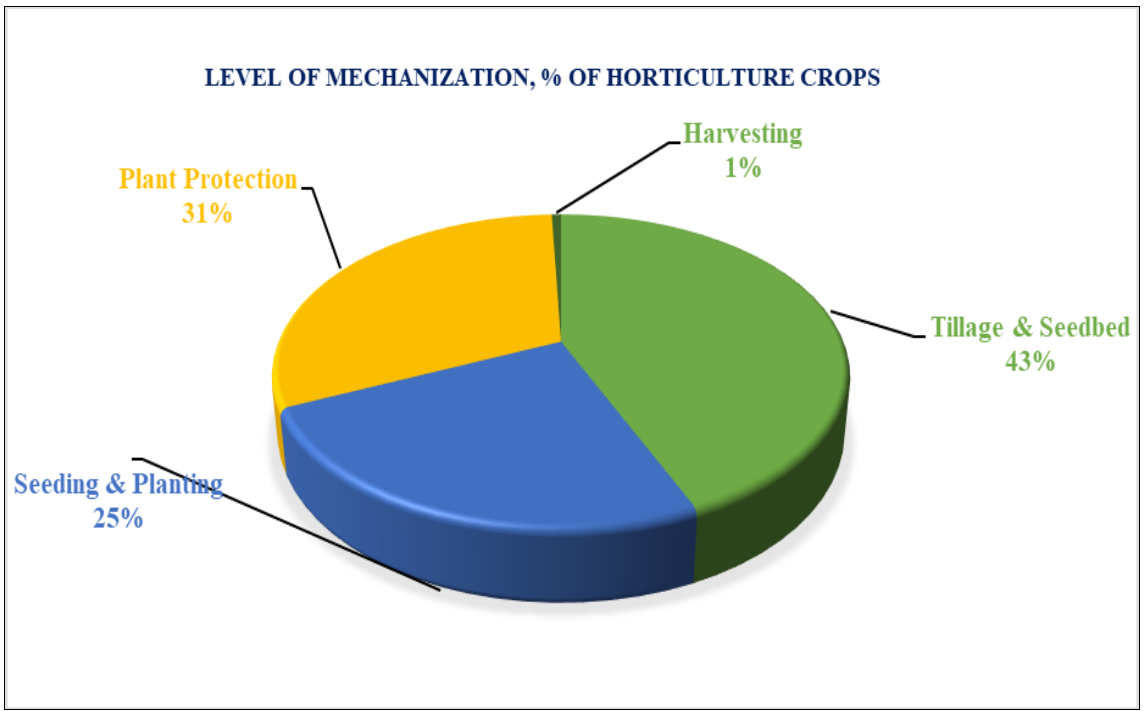


Fig 1: Level of mechanization in horticultural crops (Tiwari *et al.* 2019) [104]

Conventional methods of farm operations in seed spices crops and transformation approach for enhancing seed spices crops productivity: Most of the farm operations in the seed spices can usually done by manual methods, which leads to more time-consuming, labour-intensive, and classified as moderately heavy work. Implementing the right machinery and tools in the cultivation of seed spices can significantly enhance productivity and efficiency. In the realm of seed spice cultivation, significant advancements have been made in various operational stages, leveraging technology to enhance efficiency and yield. The transformation in farm operations of seed spice crop cultivation represents a progressive approach aimed at enhancing efficiency, productivity, and sustainability in agricultural practices. Traditionally, many farm operations in seed spice cultivation relied on manual methods, which were time-consuming, labor-intensive, and classified as moderately heavy work (Yadav, R., Patel, M., Shukla, S. P. and Phund 2007) [118]. However, by incorporating modern techniques and machinery, significant improvements can be achieved throughout the entire cultivation process.

Seedbed preparation for seed spices crops

The first step in seed spice cultivation is preparing the seed bed to create an optimal growing environment. Seedbed preparation is a critical step in establishing a conducive environment for seed spice crops that often require a fine tilth for optimal germination. Traditionally, farmers use animal-drawn ploughs to initially break the soil. This is followed by manual breaking of soil clods using hand tools such as hoes and rakes. The soil is repeatedly worked to achieve the desired fineness. Ploughs, such as mouldboard or disc ploughs, are commonly used for initial soil turning. They are effective in breaking up the soil, incorporating organic matter, and uprooting weeds. Following ploughing, harrows (like a disc or tine harrows) are employed to further break down soil clumps and smooth the soil surface, preparing a fine seedbed crucial for many spice crops (Kepner, R.A., Bainer, R. and Barger 1987) [53]. Rotavators or rotary tillers can also be used at this stage to achieve a fine tilth, enhancing soil aeration and moisture retention - key factors for seed germination (Hunt 1983) [45]. Advanced ploughing equipment like chisel ploughs or subsoilers can be used for deep tillage, which helps in breaking up compacted layers of soil, thereby improving aeration and water infiltration (Lal, R., Bandyopadhyay, R., Gao, S., & Sharma 2020) [64]. Post ploughing, harrows, such as power harrows or rotary hoes, are effective in creating a fine tilth, which is essential for small-seeded spice crops. These implements break soil clods and remove weeds, ensuring a smooth and levelled seedbed. The seed bed preparation was shown in figure 2.

Seed bed preparation has been revolutionized with implements like a driverless tractor, laser land levellers, rotary tillers, and subsoilers. The adoption of driverless tractors (Lagnelöv *et al.* 2023) [63]. Highlighted by has been a game-changer in seed bed preparation, bringing precision and efficiency to a previously labour-intensive process. These autonomous vehicles can be programmed for specific tasks like ploughing, ensuring uniform soil texture and depth, crucial for seed spices. Laser land levellers (Chen *et al.* 2022) [22] have significantly improved the evenness of the field surface. This is particularly important for spices like coriander, where even germination and water distribution are key. Jagvir, D.2006 (Jagvir Dixit 2006) [49], emphasizes the role of rotary tillers and subsoilers in preparing the soil. Rotary tillers create a fine tilth suited for small seeds, while subsoilers break up deeper soil compaction, promoting better root growth and water infiltration.

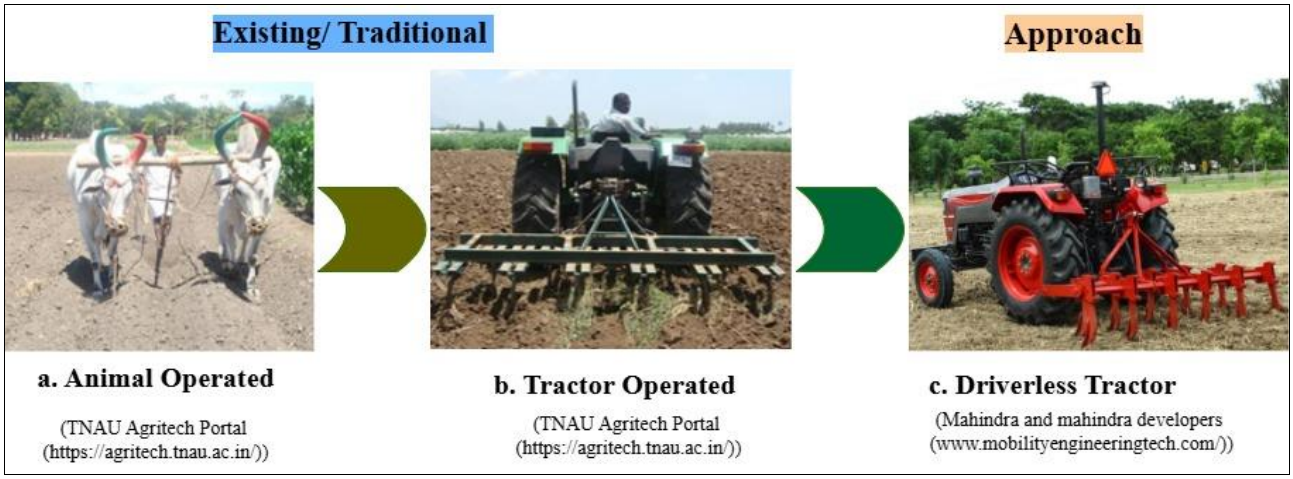


Fig 2: Transformation in seedbed preparation of the seed spices crops

Sowing / Planting of seed spices crops

Conventionally, sowing of seed spices is through broadcasting by hand is common, though it requires skill to achieve even distribution. In some regions, farmers use a 'pora' or a 'kera' (traditional hand-held seed drills) for sowing smaller seeds like cumin or mustard. These tools allow better control over seed depth and spacing compared to broadcasting. Seed rates and sowing times are based on generational knowledge and local climatic conditions. Uniform and precise sowing is crucial in seed spice cultivation. Seed drills are widely used for this purpose, ensuring consistent depth and spacing of seeds. Precision seed drills are particularly advantageous as they improve germination rates and optimize plant density (Ivančan *et al.* 2004) (Xia *et al.* 2011) [48, 113].

The sowing process has seen a shift towards precision agriculture. Vacuum planters and pneumatic seed drills (Singh *et al.* 2005) [96] (Kumar *et al.* 2015) [15] (Pareek *et al.* 2023) [80] offer precise seed placement and depth control, crucial for uniform crop growth. The use of GPS technology in sowing equipment allows farmers to maintain exact row spacing and planting patterns (He *et al.* 2021) [44]. This technology not only optimizes plant density but also facilitates subsequent farm operations like weeding and harvesting which is shown in figure 3.

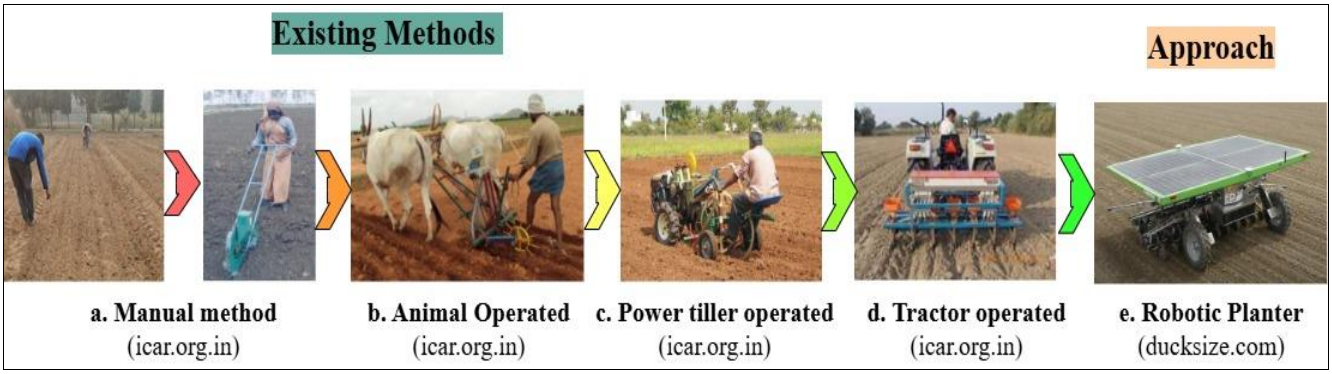


Fig 3: Transformation in sowing operation of the seed spices crops

Plant protection in seed spices crops

Similarly, conventional plant protection for seed spices primarily involves manual weeding, which is labour-intensive but crucial for these often low-growing crops. Farmers also use traditional knowledge of crop rotations and intercropping to naturally reduce pest populations. For instance, growing certain spices alongside legumes can enhance soil fertility and deter pests. Homemade natural pesticides, like extracts of neem or other locally available plants, are commonly used. The use of sprayers for the application of herbicides, pesticides, and fungicides is a critical aspect of plant protection in seed spice cultivation. Implement-mounted or tractor-mounted sprayers ensure efficient and even application of chemicals (Pramod *et al.* 2023) [82] (Vala and Yadav 2023) [107]. For mechanical weed control, cultivators are effective, offering a sustainable alternative to chemical methods. These cultivators can be adjusted to suit the row spacing and growth stage of the crop (Hussain, M., Farooq, S., Merfield, C. and Jabran 2018) [46].

In the domain of plant protection, automated sprayers and drones ensure precision application of targeted pesticides and herbicides, minimizing chemical usage and environmental impact and reducing exposure risks (Yallappa *et al.* 2017) [119] (Zhang *et al.* 2023) [123]. Drones are particularly effective in large or difficult-to-reach areas. Additionally, sensor-based technology is being used for the early detection of diseases and pests, allowing for timely and precise interventions, which is critical in maintaining the health of spice crops(Subramanian *et al.* 2021) (Abbas *et al.* 2023) [1, 101]. The various plant protection sprayers shown in figure 4.

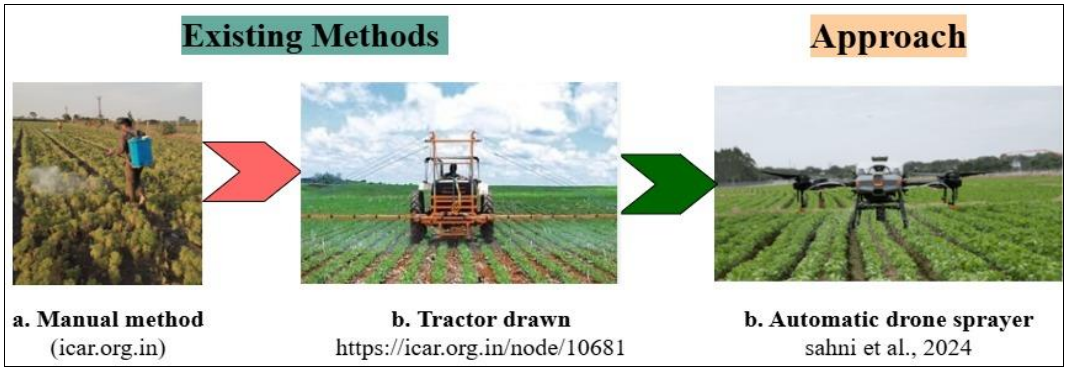


Fig 4: Transformation in crop protection/spraying operation of the seed spices crops

Harvesting of seed spices crops

Traditional harvesting is predominantly a manual process. Farmers use hand tools like sickles to harvest the crops (Alam 2002) [2] (Lal *et al.* 2014) [65]. Manual harvesting is time-consuming, labour intensive, and classified as moderately heavy work (Yadav, R., Patel, M., Shukla, S. P. and Phund 2007) [118]. The labour-intensive harvesting operation incurs additional expenditures, reducing farmer profits. As a consequence, a mechanical harvesting method is required to deal with the rising area of crop-producing land (Kiran, I. K. M., Awal, A, M. and Ali 2017) [59]. This method is labour-intensive but allows for selective harvesting, which is crucial for many seed spices that mature unevenly. Threshing is also typically done by hand or using simple tools, a process that is time-consuming but gentle on the seeds. Drying is done naturally, with the harvested spices spread out in thin layers under the sun, which requires careful monitoring to prevent overexposure or moisture ingress.

Harvesting techniques have evolved with the introduction of semi-automated harvesters and robotic picking systems (Iida *et al.* 2013) [47] (Silwal *et al.* 2017) [94] (Xiong *et al.* 2020) [115]. These technologies ensure the gentle handling of crops, minimizing damage and optimizing yield which is shown in figure 5. This approach not only improves efficiency but also reduces the labour-intensive nature of traditional harvesting (Eberhardt and Vollrath 2018) (Wang, Yang, *et al.* 2019) [32, 108, 110].

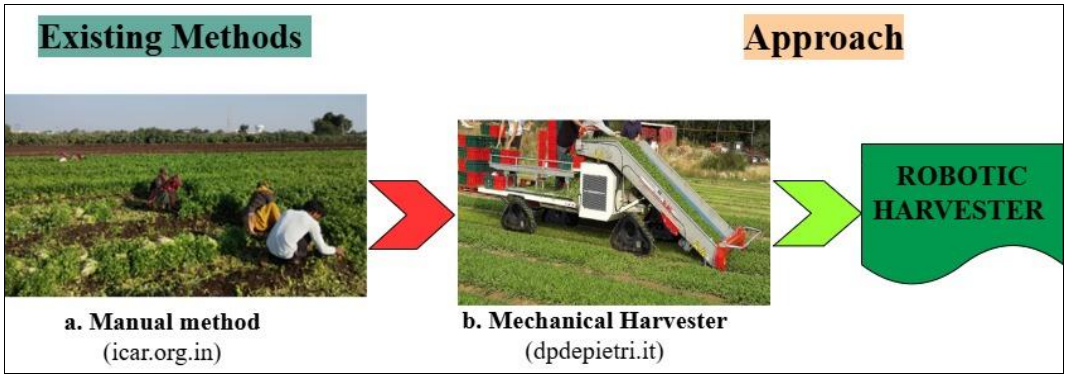


Fig 5: Transformation in Harvesting of the Seed Spices Crops

Challenges in conventional farming operations in seed spices cultivation: In seed spices cultivation, from seedbed preparation to harvesting faces numerous challenges, impacting efficiency, quality, and profitability (Alam 2002) [2] (Momin and Jamir 2021) [75]. Each stage presents limitations across various methods, including manual labor, animal power, and tractor-based tools. Seedbed preparation relies on manual labor or animal-drawn implements, resulting in slow progress, limited area coverage, and potentially uneven tilth, while tractor-powered solutions offer faster coverage but come with drawbacks such as high initial investment, fuel dependence, and risk of soil compaction (Kumar *et al.* 2023) [61]. Despite the potential for faster coverage, tractor-powered solutions come with their own set of drawbacks, including high initial investments, dependence on fuel, and risks of soil compaction (Mehta *et al.* 2014) [71] (Priyadharsini *et al.* 2021) [83]. Similar challenges persist during sowing, crop protection, and harvesting stages, exacerbating issues related to accuracy, effectiveness, and labor intensity. The labour-intensive nature of seed spices cultivation significantly affects worker health, leading to elevated heart rates (110-140 bpm), and increased oxygen operations such as manual weeding and harvesting (Table.1). These physical demands contribute to the prevalence of musculoskeletal disorders (MSDs) among workers, including lower back pain, shoulder strain, and wrist injuries. Ergonomic interventions and mechanization are crucial to mitigate these health risks and improve labor efficiency. Additionally, adopting robotic automation presents a promising solution to these challenges. Automated systems can perform precise planting, weeding, and harvesting, reducing the need for manual labor and minimizing health risks (Cheng *et al.* 2023) [23]. Robots equipped with advanced sensors and AI can adapt to various farming conditions, enhancing efficiency and productivity (Blackmore, S., Stout, B., Wang, M., & Runov 2005) [11, 111]. To address these multifaceted challenges and ensure the sustainable success of seed spice cultivation, exploring innovative tools, including robotic automation and mechanization tailored to specific crops, is essential. Investing in research for resilient crop varieties and providing education and training for farmers on modern farming techniques will drive positive change in the industry, enhancing both productivity and worker well-being. The conventional method challenges were shown in figure 6.

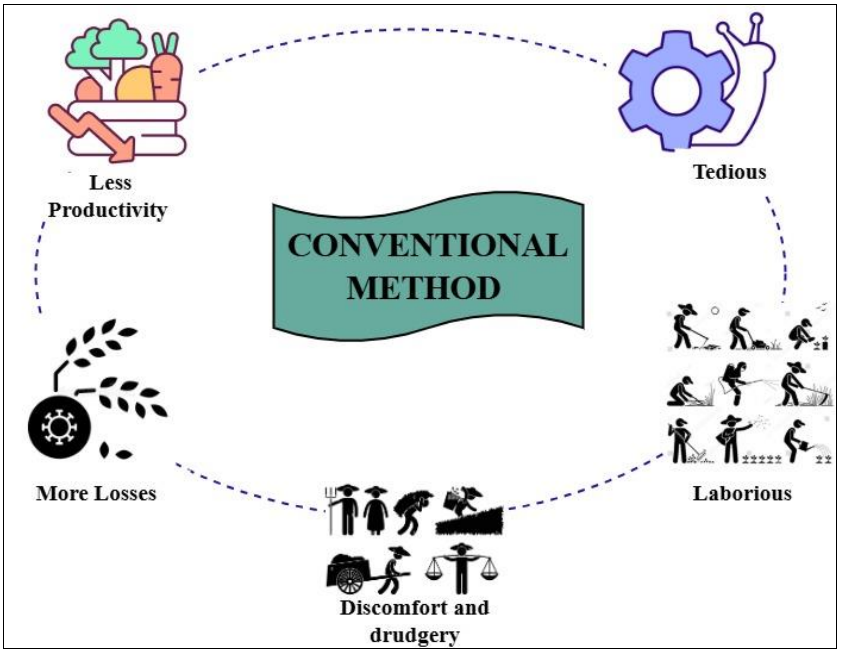


Fig 6: Challenges in conventional methods of seed spice crop cultivation

Table 1: Physiological response for different operations in the seed spices cultivation

Operation	Heart rate (bpm)	VO_2 Consumption (L/min)	Energy Expenditure (kJ/min)	Ref.
Seedbed preparation				
Manual	130-160	1.8-2.5	20-30	(Chen *et al.* 2004) (Jagvir Dixit 2006) [21]
Animal	100-130	0.4-0.7	10-18	
Tractor	80-110	0.8-1.2	200-250	
Sowing				
Manual	110-150	0.5-1.8	10-40	(Ivančan *et al.* 2004) [48]
Animal	110-140	1.2-1.8	350-400	
Tractor	80-110	0.8-1.2	200-250	
Weeding				
Manual	90-130	0.58-1.7	10-15	(Singh 2016) (Jagvir Dixit 2006) [95]
Animal	120-140	1.5-2.0	350-450	
Tractor	90-110	1.0-1.5	200-300	
Spraying				
manual	90-110	0.4-0.70	10-15	(Palmer *et al.* 2003) (Jat *et al.* 2023) [50, 79]
Animal	110-130	1.8 to 2.3	8-10	
Mechanical	-	-	-	
Harvesting				
Manual	90-120 (Sickle)	0.45-0.75	15-25	(Ramin Shamshiri *et al.* 2018) (Singh 2016) [84, 95]
Animal	120-140	2.0 to 2.8	-	
Mechanical	110-130	-	19-23	

Scope of advanced technologies in the cultivation of seed spices crops: Traditional seed spice cultivation faces numerous limitations, impacting efficiency, quality, and sustainability. Advanced technologies, including driverless systems and robotics, offer a ray of hope, holding immense potential to revolutionize various stages of the cultivation process, from seedbed preparation to harvesting and beyond. Enhanced precision and efficiency are achieved through techniques like precision agriculture, where driverless tractors, robotic planters, and drone-based soil analysis promise pinpoint accuracy in seedbed preparation, sowing, and resource management, optimizing yield and minimizing waste (Iida *et al.* 2013) (Lagnelöv *et al.* 2023) (Xiong *et al.* 2020) [47, 63, 115].

AI-powered solutions further enhance precision, with seed drills guided by AI algorithms and robotic weeders equipped with image recognition ensuring optimal seeding depth, targeted weed control, and reduced reliance on herbicides (Wu *et al.* 2020) [112]. Additionally, deploying teams of small robots for tasks like weed control, irrigation, and data collection through swarm robotics offers efficient solutions while minimizing soil disturbance (Zhang *et al.* 2022) [122] (Sharifnasab *et al.* 2023) [92]. Sustainable practices and environmental protection are furthered by wireless sensor networks enabling real-time monitoring of soil moisture and nutrient levels, facilitating precision irrigation and reducing water waste and environmental impact. Moreover, drone-based spraying allows targeted application of pesticides and fungicides, minimizing environmental impact and ensuring optimal pest control compared to traditional methods (Subramanian *et al.* 2021) [101] (Yallappa *et al.* 2017) [119]. Utilizing natural enemies of pests delivered by drones or robots offers a sustainable alternative to harmful chemicals, promoting ecological balance. Improved quality and reduced losses are achieved through robotic harvesters equipped with advanced grippers and sorting mechanisms, selectively harvesting mature seeds, minimizing damage, and ensuring consistent product quality.

The integration of these technologies also significantly enhances worker comfort and safety. Automated systems reduce physical strain by performing labor-intensive tasks, thereby lowering the incidence of musculoskeletal disorders (MSDs) and other health issues related to manual labour**.** Ergonomically designed machinery and equipment further reduce physical strain, enhancing worker safety and productivity. Despite the vast scope of advanced technologies, challenges such as initial investment costs, infrastructure development, and access to skilled personnel remain. The scope of advanced technologies were shown in figure 7. Collaborative efforts between researchers, farmers, and technology developers are crucial to overcoming these hurdles and making these advancements accessible and affordable for the seed spice sector. Embracing these innovations has the potential to transform seed spice cultivation into a more efficient, sustainable, and productive endeavors, ensuring the long-term success of this vital agricultural sector while safeguarding the environment and human well-being. The various advanced technologies were shown in table 2.

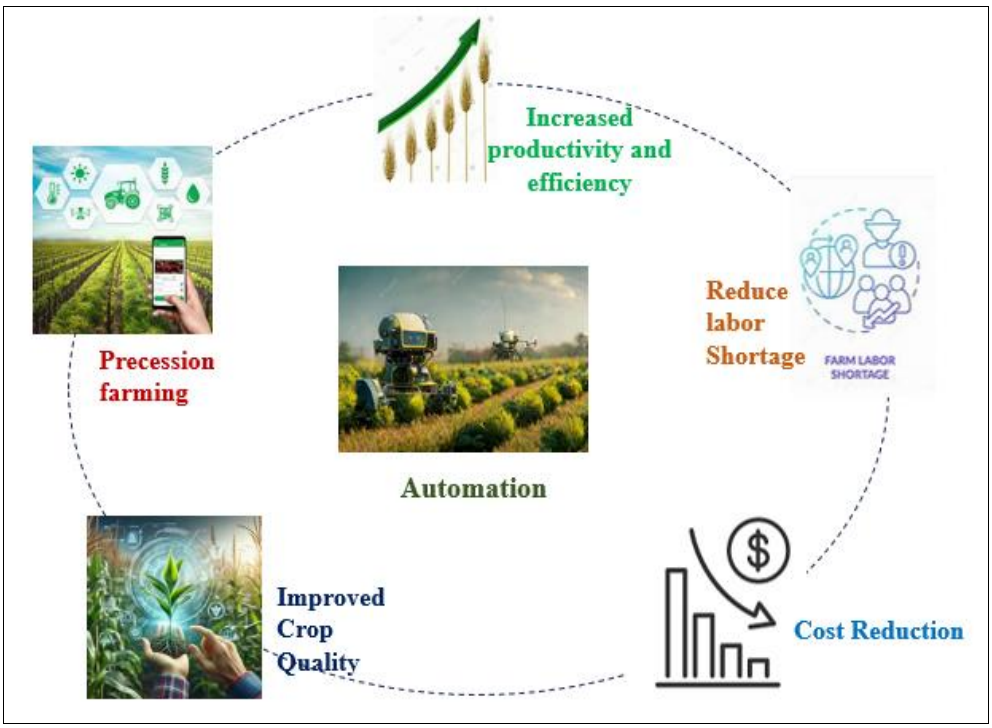
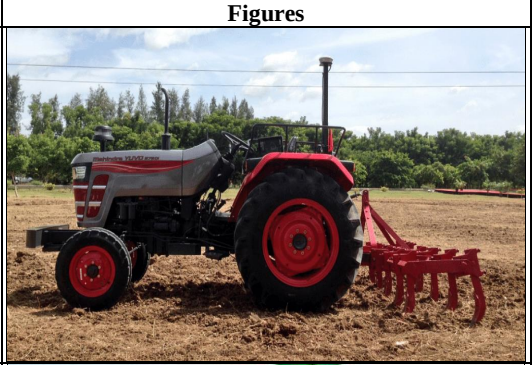


Fig 7: Scope of advanced technologies in seed spices crop cultivation

Table 2: Improved technologies can adopt for the seed spices cultivation to increase productivity, comfort and safety.

Operation	Method/ Machines	Figures	Ref.
Seedbed preparation	Driverless tractor		(Kim *et al.* 2018) (Li *et al.* 2020) (Zhang *et al.* 2024) [57, 67, 121]
Sowing	Robotic planters		(Ayanniran *et al.* 2024) (Khadatkar *et al.* 2023) (Zheng *et al.* 2021) (Amer *et al.* 2020) (Ugargol *et al.* 2022) [3, 5, 55, 106, 124]

Weeding	Robotic weeders			(Pedersen *et al.* 2005) (Gagliardi *et al.* 2021) (Xiong *et al.* 2017) (Reiser *et al.* 2019) [36, 81, 85, 116]
Spraying	Robotic sprayers and Drones			(Chen *et al.* 2020)(Ghafar *et al.* 2021)(Jat *et al.* 2023)(Kassim *et al.* 2020)(Meshram *et al.* 2022) [20, 22, 38, 50, 52, 73]
Harvesting	Robotic harvester			(Sirikun *et al.* 2021) (Kurita *et al.* 2017) (Xiong *et al.* 2020) (Dimitrov *et al.* 2019) [28, 62, 98, 115]

Scope of Robotics in Crop Cultivation Practices

Several ideas in the literature exist about how robots could help with agricultural tasks. Indeed, one of the most important ways to combat population expansion is to mechanize and automate agricultural tasks. Khadatkar *et al.*, (Khadatkar *et al.* 2022) [54] highlighted the robotic systems accessible for different farm activities, technology, and methodologies for horticulture and field crops.

Agricultural robots perform general operations similarly for crops similar to one another and slightly differently for crops that are not. It is crucial to talk about the framework for agricultural robots that are adaptable to different crops. Automation of several agricultural tasks, including sowing, planting, weeding, spraying, harvesting, scouting, picking, plant phenotyping, thinning, and mowing is possible using robots. Machine vision systems or computer graphics are utilized by robotic transplanters, planters, and seed drills to perform sowing and planting operations. Robotic planters primarily consist of a robotic arm for picking up seedlings, an end-effector, and a route manipulator (Wang, Lan, *et al.* 2019) [108] (Xin *et al.* 2018) [114]. Similarly, robotic weeders use vision-based weed detection systems to physically uproot weeds (Meng *et al.* 2015) [72] (Midtiby *et al.* 2016) [74]. Gonzalez-de-Soto *et al.*(Gonzalez-de-Soto *et al.* 2016) [39] demonstrated patch spraying using robotic methods, enabling precise application of herbicides. Moreover, most robotic harvesters are designed to harvest fruits, operating by using grippers to hold the fruit and then separating it based on texture, size, color, and shape (Wang, Lan, *et al.* 2019) [108]. The same robot can accomplish this by changing its attachments, choosing a new robotic perception software, and picking an unlike end-effector for the innovative task. This category of robot is known as an intelligent agricultural robot with multiple functions (MIAR) (Cheng *et al.* 2023) [23].

Navigation in Agricultural Robotics

Agricultural robots rely on efficient navigation systems to move around the farm, navigate through fields, and perform tasks with precision. Navigation technologies such as GPS, sensors, and mapping systems enable robots to localize themselves, avoid obstacles, and optimize their routes. Accurate navigation is crucial for agricultural robots to efficiently perform tasks such as planting, spraying, and harvesting, with studies showing that navigation errors can result in significant yield losses (Wang, Yang, *et al.* 2019) [108].

Guidance and Path Planning

The path planning is a crucial aspect of agricultural robotics, enabling robots to navigate fields safely and efficiently while avoiding damage to crops (Fue *et al.* 2020) [34]. This process involves determining the optimal path for the robot to follow and scheduling the movement of manipulators to reach their destination**.** In essence, path planning involves deciding how to steer and manipulate the robot to complete tasks based on sensory data**.** Various path-planning algorithms have been developed for robotics systems, including reward-based, artificial potential fields, geometric, and interval-based search

algorithms (Jaulin 2001) [51]. While each algorithm has its applications, sampling-based algorithms are particularly effective in high-dimensional spaces, offering greater flexibility and accuracy. As agricultural robots increasingly operate in swarms, real-time path planning and motion control are essential for governing and limiting the movements of swarm mediators**.** However, navigating dense crops like cotton poses significant challenges due to overlapping leaves (Fue *et al.* 2020) [34]. In contrast, robots can easily navigate between rows in larger plants like citrus and harvest fruit from the other side of the row (Subramanian *et al.* 2006) [100].

To optimize navigation, robots must coordinate their SLAM movements between rows to avoid repetition and arrange their arm movements to avoid cutting branches**.** Effective path planning is critical for agricultural robots to efficiently complete tasks while minimizing crop damage**.** According to experts Khadatkar et al; Santos *et al.*, (Khadatkar *et al.* 2022) [54] (Santos *et al.* 2020) [89], path planning algorithms in agriculture can be broadly classified into two primary groups: point-to-point path planning and path planning coverage. Point-to-point path planning aims to optimize metrics such as time, distance, or energy by finding a collision-free path between a starting point and a destination, useful in applications like autonomous farming vehicles. Path planning seeks to find a path that avoids obstacles and covers every point in a given area, essential for crop spraying, fertilizing, and harvesting Galceran and Carreras, Cao *et al.* (Galceran and Carreras 2013) [37] (Cao *et al.* 1988) [17] first outlined the essential requirements for coverage operations. Santos *et al.* (Santos *et al.* 2020) [89] successfully implemented path planning for point-to-point navigation and field coverage in agricultural robots.

Steering and mobility

The steering and mobility are critical aspects of agricultural robotics, significantly impacting their efficiency and effectiveness in crop cultivation. Most agricultural robots are equipped with either legs or wheels, each offering distinct advantages and suited to different farming conditions. Wheeled robots provide quicker and simpler navigation, making them ideal for smooth and even terrains. They offer rapid and economical field operations and have become increasingly common due to their speed and ease of use (Bakker *et al.* 2010) [7] (Lei *et al.* 2023) [66]. However, wheeled robots can struggle with uneven surfaces, traction issues, and obstacles like branches and stems, which can impede their movement. In contrast, legged robots excel in navigating uneven terrains and dealing with obstacles such as cracks, branches, and stems. They offer greater flexibility and adaptability in varied agricultural environments, making them more successful on diverse terrains despite their slower speed (Auat Cheein *et al.* 2011) [4]. These robots are particularly useful in marshy fields or areas with significant plant obstructions (Bayar, R., Abdelkhalek, A., Dhouib, A., & Derbel 2018) [8]. Drones are primarily used for spraying, scouting, and monitoring crops from the air. They offer extensive spatial sensing capabilities but are less effective for tasks requiring direct interaction with plants, such as pruning and harvesting (Reiser *et al.* 2019) [85].

Combining drone data with terrestrial robotic systems enhances scouting efficiency and allows for more effective navigation and task execution (Chlingaryan *et al.* 2018) [24]. Specialized robotic systems are designed for specific tasks: rail-based robots are ideal for fast navigation in controlled environments like phenotyping experiment while cable-oscillating robots such as the Tarzan robot and Ag Ant, which oscillate on cables over crops, are preferred for detailed inspections in marshy areas and close examinations of plants (Duarte, M. F., Faria, A., & Rodrigues 2017) [30]. For tasks such as weeding on slippery surfaces, robots like the Fuji Agricultural robot and rack-like robots are used to minimize skidding. The Dogtooth robot, used for harvesting strawberries, follows a predefined path within a greenhouse, optimizing its movement and efficiency (Duckett *et al.* 2018) [31].

Four-wheel guided robots (SwagBot, Thorvald II, and Agribot) are essential in environments where tire traction is problematic, such as muddy fields or feedlots**.** For routine agricultural tasks, two-wheel rotating robots are generally sufficient, offering simplicity and efficiency for everyday operations**.** Skid-steer robots link the wheels on one side to drive and steer, making them suitable for row crop production. These robots are designed to operate autonomously, even if certain sensors (cameras, IMUs, or GPS) fail, ensuring continuous operation (Xue *et al.* 2012) [117] (Bayar, R., Abdelkhalek, A., Dhouib, A., & Derbel 2018) [8]. Simple models of movable robots resembling cars can effectively demonstrate motion and steering in unmanned agricultural robots (Auat Cheein *et al.* 2011) [4] (Cheein, F. A. A., Guivant, J. E., & Carelli 2010) [19]. Field implementation of these robots involves several procedures: mapping the field, programming the robot for specific tasks, integrating sensors for navigation and obstacle detection, and ensuring real-time data processing for autonomous operation (Cai, G., Jiang, Z., Li, J., & Wang 2021) [14].

Robots are programmed to perform tasks such as planting, weeding, and harvesting, utilizing advanced algorithms for path planning and obstacle avoidance (Reiser *et al.* 2019) [85] (Bergerman, M., Freitas, G., Hamner, B., Keller, C., & Kantor 2016) [10]. Studies and field trials have demonstrated the effectiveness of these robots in improving agricultural productivity and reducing labour costs (Burud, I., Thiis, T., Boge, J., Nordal, J. H., Øverli, J., & Andersen 2017) [13]. By understanding the strengths and limitations of different steering and mobility systems in agricultural robots, farmers can optimize their use in crop cultivation, selecting appropriate robotic systems for specific tasks and ensuring efficient and effective agricultural practices across various field conditions.

Self- localization and Sensing

The self-localization and sensing enable agricultural robots to navigate and interact with their environment, allowing them to accurately identify and respond to crop needs, detect pests and diseases, and optimize farming practices (Bechar and Vigneault 2016) [9]. Received Signal Strength Indicator (RSSI)-based distributed self-localization is a technique that can be used for wireless sensor networks (WSNs) in precision agriculture, which uses received signal strength indicator (RSSI) values to estimate the distribution of distance between nodes. Sensing updates the system on its surroundings so that it can find its way around or harvest fruits**,** identify pests, weeds, or diseases, regulate the height at which it sprays above the plant canopy, and accomplish other functions. To perform well in dynamic situations with varying vegetation, fluctuating weather, unforeseen obstructions, and topographical changes, the robot needs robust sensing systems.

To achieve localization, the majority of agricultural robots now in use rely on Global Navigation Satellite technologies (GNSS) and image sensing technologies (Table.3). The ability to perceive and produce three-dimensional, two-dimensional, and four-dimensional (spatial + temporal) images of plants has greatly increased due to the development of imaging technology

(Md Matiur *et al.* 2015) [70]. Agricultural fields have utilized numerous sensors, including near-infrared, visible light, fluorescence, thermal, spectroscopy, color infrared, digital imaging (RGB), hyperspectral, multispectral, spectroradiometer, thermal, spectrometer, moisture, sound navigation and ranging (SONAR), light-reflective, pH detector, light detection and ranging (LIDAR), electrical resistance tomography, and ground-penetrating radar, to obtain a two-dimensional, three-dimensional, and four-dimensional perception of the environment (Deery *et al.* 2014) [26] (Dong *et al.* 2017) [29] (Sankaran *et al.* 2015) [88] (Sun *et al.* 2017) [102]. Further sensors have been used to provide navigation feedback and robot direction, including piezoelectric yaw, acoustic, pitch and roll rate, mechanical, inertial, optical encoder, ultrasonic, RF receiver, piezoelectric rate, Geomagnetic Direction Sensor (GDS), laser range finder (LRF), Near Infrared (NIR), piezoelectric yaw, and Fiber Optic Gyroscope (FOG) (Fue *et al.* 2020) [34] (Mousazadeh 2013) [76]. The target's unique qualities relative to the rest of the obstacle-rich environment influence the imaging sensor selection to some extent. If it is possible to visually identify the target on the field, standard digital photography may be utilized. For instance, distinguishing green bell pepper or citrus from a population of green vegetation may necessitate the use of a different sensor or the detection process may become more complex by using sophisticated machine-learning techniques (Choi *et al.* 2017) (Zhu *et al.* 2018) [25, 125].

Changes in illumination, clutter, camera motion, temperature swing, motion, deformation, scene complexity, and wind movements necessitate the use of specific image-refining methods to improve the photos. The next step involves applying machine vision techniques such as pattern recognition to accomplish recognition of objects or feature extraction. Morphological process and filters (Manchikanti and Sengupta 2011) [69], image color space-changing (Tao *et al.* 1995) [103], image smoothing and segmentation (Hannan *et al.* 2007) [42] (Fue *et al.* 2018) [35], illumination normalization(Wang *et al.* 2018) [109], grey level concurrence matrix (Chang *et al.* 2012) [18], rapid bilateral screening method based Retinex**,** and normalized co-occurrence matrix are just a few of the techniques for image rectification and enhancement to date. It is possible to extract features through traditional image processing methods or more sophisticated machine learning methods like masking and color filtering. Robot sensors must identify and locate themselves in the environment after detecting their surroundings for the robot to make navigational decisions and arrive at its destination.

In agriculture, GPS and machine vision have been utilized to identify the place and even assist the robot in moving over or in between crop rows, as well as turning toward the end of the row. To choose whether to move, the robot must make a snap judgment during localization. In doing so, the mission requires the use of simultaneous localization and mapping (SLAM) methods (Bergerman, M., Freitas, G., Hamner, B., Keller, C., & Kantor 2016) [10]. Operating systems (ROS) and wireless sensors for data transmission between sensors and controllers could be beneficial in a small robot. Nevertheless, several factors, including the data rate, radio transmission standard being used, slave enumeration latency, nodes permitted per master controller, complexity, the transmission range, the type of data to be transmitted costs, sensor battery life, and extendibility may have an impact on wireless transmission (Wang *et al.* 2006)**.**

Table 3: Navigation of Robotics in Agriculture

Activity	Mobility	Sensing	Path Planning	Manipulator	Ref.
Soil sampling	Four-wheel (BoniRob)	Soil moisture and RTK-GPS	Grid-based GPS tracking	2 DOF Penetrometer	(Scholz *et al.* 2014) [91]
	Four-wheel (Thorvald)	Force and soil moisture sensor, measurement device, TK-GPS	Grid-based GPS tracking	2 DOF Penetrometer	(Fentanes *et al.* 2018) [33]
	Two-wheel	encoder, GPS	Adaptive grid-type navigation GPS tracking	2 DOF Cone penetrometer and Linear actuator	(Cao *et al.* 2003) [16]
Sowing	Continuous track	Ultrasonic sensor, magnetometer	Navigation by senor data	2 DOF Sowing device	(Srinivasan *et al.* 2017) (Haibo *et al.* 2015) [41, 99]
	Four-wheel	Encoder, IR, pressure, and angle sensor	Path tracking	2 DOF Sowing device	
Weeding	Continuous track	LRF and IMU	Path tracking	2 DOF	(Kim *et al.* 2012) [58]
	Four-wheel	GPS, magnetometer, camera, gyroscope	Path tracking, adaptive and strategic planning	N/A	(Bak and Jakobsen 2004) [6]
	Four-wheel	GPS, angle sensor, camera	Hough transfer technique for row detection	N/A	(Bakker *et al.* 2010) [7]
Spraying	Four-wheel	Laser and ultrasonic sensor, stereo camera, GPS, encoders	Path tracking with trajectory plan	N/A	(Cantelli *et al.* 2019) [15]
	Four-wheel	GPS, LRF, and magnetic sensor	Self-positioning and path tracking	N/A	(Nakao *et al.* 2017) [77]
	Four-wheel	Temperature, soil moisture and humidity sensor, camera, GSM modem	N/A	N/A	(Sharma and Borse 2016) [93]
	Rails sliding	Bump, IR and induction sensor	N/A due to vehicle sliding on rails	N/A	(Sammons *et al.* 2005) [87]
Pruning	Four-wheel	3D measurement devise and sensor	Grid-based innovative climbing	2 DOF	(Ueki *et al.* 2011) [105]
	Four-wheel	3D camera	Randomized path planning	6 DOF	(Botterill *et al.* 2017) [12]
	Two-wheel	N/A	Climbing method	9 DOF	(Devang, P.S., Gokul, N.A., Ranjana, M., Swaminathan, S.,

					Binoy, B.N. 2010) [27]
	Four-wheel with regular interval	N/A	Climbing method	2 DOF	(Haruhisa Kawasaki, Suguru Murakami, Hideki Kachi 2008) [43]
Phenotyping or scouting	Continuous track	Optical encoder, IR sensor, gyroscope, RGB Stereo camera, RTK-GPS, ToF sensor	Controller: nonlinear model predictive	N/A	(Young *et al.* 2019) [120]
	Four-wheel	RGB camera, 3D IMU, GPS, LIDAR, 2D security lens	Mapping with real-time localization	N/A	(Obregón *et al.* 2019) [78]
	Four-wheel	RTK- GPS, RGB stereo camera	GPS auto-steering	N/A	(Gutiérrez-Grijalva *et al.* 2018) [40]
	Four-wheel	NIR camera, RTK-GPS, RGB multicamera	GPS auto-steering	N/A	(Kicherer *et al.* 2015) [56]

(N/A indicates that the author has not provided any data)

Conclusion

The adoption of advanced technologies holds immense potential for transforming seed spice cultivation in India. Traditional methods, relying on manual labor and rudimentary tools, are often labor-intensive, inefficient, and prone to errors. These limitations lead to reduced crop yields, decreased quality, and increased waste. In contrast, precision agriculture, robotics, and data analytics can improve crop yields, reduce water consumption, and lower costs. Autonomous systems and advanced sensing and navigation systems can enhance crop monitoring, harvesting, and processing efficiency, while robotic automation can improve product quality. Moreover, precision agriculture can optimize crop water management, reduce fertilizer application, and minimize environmental impact. To realize this potential, stakeholders must collaborate to overcome infrastructure and skill barriers. We urge policymakers, industry leaders, and farmers to invest in and adopt these technologies, driving innovation and sustainability in the seed spices sector and ensuring a prosperous future for Indian agriculture.

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Data availability

There is no extra data other than the data mentioned in this manuscript.

Author contributions

Aruna T.N Conceptualization, investigation, methodology, formal analysis, writing-original draft, writing-review and editing; P.K. Sahoo Investigation, methodology, formal analysis, writing-review and editing; D.K. Kushwaha Investigation, methodology, formal analysis, writing-original draft; Kishan kumar Methodology, writing-review and editing, supervision, project administration; N C Pradhan Formal analysis, writing-original draft, writing-review and editing; Soumya Krishnan V Formal analysis, writing-original draft, writing-review and editing; Avesh K. S Formal analysis, writing-original draft, writing-review and editing; Rohit G Formal analysis, writing-original draft, writing-review and editing; Ramya C.S Formal analysis, writing-original draft, writing-review and editing.

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