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Review article

Hydroponics: Exploring innovative sustainable technologies and applications across crop production, with Emphasis on potato mini-tuber cultivation

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ABSTRACT

There is an urgent need to explore climate-resilient alternative agriculture production systems that focus on resilience, resource efficiency, and disease management. Hydroponics, a soilless cultivation system, gaining interest as it reduces the dependency on agricultural land, and pesticides, and can be implemented in areas with poor soil quality, thus mitigating the negative effects of extreme weather events. Potato is an essential dietary staple crop grown throughout the world and is a major source of food security in underdeveloped countries. However, due to the climatic changes, it is predicted that a significant loss in the suitability of land for potato production would occur, thus leading to potato yield loss. Recently, many case studies have emerged to highlight the advancement of agricultural hydroponic systems that provide a promising solution to the massive production of potato mini tuber at high efficiency. This review paper evaluates popular hydroponic methods and demonstrates how hydroponic has emerged as the go-to, long-term, sustainable answer to the perennial problem of insufficient access to high-quality potato seed stock. The paper discusses the research and innovation possibilities (such as artificial intelligence, nanoparticles, and plant growth-promoting rhizobacteria) that potentially increase tuber production per plant under optimal hydroponic growth circumstances. These approaches are examined considering new scientific discoveries and practical applications. Furthermore, it emphasizes that by enduring significant reforms in soilless food production systems (particularly for potatoes), the food supply of a rapidly growing population can be addressed. Since hydroponics systems are productive and easily automated without soil and optimal environmental conditions, future hydroponics farming is promising. In conclusion, the hydroponics system provides better yield and crop productivity by saving water, energy, and space. Henceforth, it can be the alternate choice for modern sustainable agriculture.

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1. Introduction

Sustainable agricultural practices safeguard the food supply and the land, and ensure global food security by addressing the challenges posed by climate change. Hydroponic, is an alternative agriculture production system that focuses on climate resilience, efficient resource utilization, and disease-free crop production [1]. In hydroponics, instead of soil, plants receive a nutrient-rich water solution directly, providing them with the essential elements they need for growth. This method has several advantages, including better control over nutrient levels, more efficient use of water, and the ability to grow plants in areas with poor soil quality [1–3].

Potato (*Solanum tuberosum* L) is a crucial agricultural crop used globally for its nutritional value [4]. Following wheat, rice, and maize, it is the fourth most significant agricultural commodity [5]. Potato is an annual herbaceous plant being cultivated in temperate climates. It was found to have originated in the Andean highlands of South America and belonged to the Solanaceae family. So far, it is regarded as one of the most valuable staple crops and vegetables since they are reasonably inexpensive to cultivate and are rich in nutrients. Fresh potatoes contain 75–80% water, 2.5–3.2% protein, 16–20% carbohydrates, 0.8–1.2% minerals, 0.6% crude fiber, 0.1–0.2% crude lipids, and specific vitamins. Despite its low protein content, it has a higher nutritious value than cereals [6]. Additionally, it includes amino acids such as isoleucine, leucine, and tryptophan [7].

The universal appeal and acceptance of potatoes across cultural boundaries suggest that may play a role in the global effort to eradicate hunger. However, in order to meet the growing demands of a growing population, the production efficiency must be increased. In many countries, the price of cultivating seed tubers might make up as much as half of the total cost of harvesting and processing, which poses a significant challenge to potato farming [8]. Mini tuber production is the fundamental approach for potato seed production since it relates the rapid multiplication of *in vitro* plantlets by nodal cuttings to the field for the multiplication of potatoes [9]. Mini tubers, which range in size from 5 to 25 mm, are harvested year-round. Rooted micro plants grow under optimum conditions to produce mini tubers and multiply over several generations to produce seed potatoes. Critical factors that can be modified during the mini tuber production phase include 1) the number of mini tubers per unit area, 2) the number of mini tubers per *in vitro* plantlet, and 3) mini tuber yield per plantlet, 4) mini tuber's average weight, and 5) the yield per unit area of mini tuber [10].

In most developing countries, practitioners traditionally used varying growth media such as perlite mixtures, peat moss, or bare soil to cultivate mini potato tubers. The most significant limitation of using soil as a growing medium is the difficulty in managing weeds and disease prevalence [11]. However, the economic implications of soilless agriculture as a replacement are significantly raised because it decreases soil disinfection and boosts water usage efficiency [12]. Hydroponics, a soilless system, has recently attracted researchers to overcome the limitations faced in traditional soil-based cultivation since it can be used for the production of crops irrespective of soil environment. Hydroponic systems, other than providing disease-free mini tubers, can provide multifold yield of seed potato as compared to the conventional methods [13,14].

Accordingly, this review aims to analyze the quintessential questions surrounding hydroponic systems and identify prospects for their field use while considering what has recently been proved, keeping potato mini-tuber production in focus. From a scientific perspective, the paper interprets two factors (nutrients and substrate) that have been extensively studied but still need more investigation since this information is crucial for enhancing nutrient acquisition management in soilless systems. Additionally, smart agriculture may make it possible for farmers to use cutting-edge technologies like artificial intelligence (AI), nanoparticles (NPs), plant growth-promoting rhizobacteria (PGPR), and aeroponics [15].

1.1. *Transition from a soil-based to a soilless production system*

Drought, unpredictable weather, contaminated water sources, and undernutrition crops compelled producers to look for alternatives to soil-based agriculture (Table 1). In response, soilless agriculture, a revolutionary crop cultivation method, has been adopted by growers for the past few decades to overcome the shortcomings faced by soil-based cultivation [16]. In comparison to soil-based cultivation, the soilless technique is considered safer since it contains fewer or no soil-borne pathogens and pests. In the soilless system, cultivation occurs in a nutrient solution or a customized cultivation substrate, including minerals [2]. The cultivation depends on using proper equipment, and the crops that are produced may generate higher yields if the system is appropriately managed.

Table 1
Characteristics of traditional soil-based farming and soilless farming.

	Characteristics	
	Traditional soil-based farming	Soilless farming
Production	• Yield- Depends on soil conditions and treatments • Good Manufacturing Practices- Depends on the soil and managing skills • Sanitation- Low quality water pose contamination risk	• Yield- Extremely high with dense crop cultivation • Good Manufacturing Practices- Depends on the supply of nutrients to plants • Sanitation- Contamination risk is less
Nutrient	• Distribution- vary with quality of soil •Utilization Efficiency- Good	• Distribution- Nutrition supply is ensured at the root zone. Monitoring and additional handling skill is required • Utilization Efficiency- No leaching and hence nutrients are uniformly distributed
Water Use	• Efficiency- Susceptible to soil conditions •Salinity- Build-up of salt	• Efficiency- supply of water is controlled via sensors • Salinity- Salt flushing makes more water requirement
Management	• Labour and Equipment- Needed for ploughing and harvesting	• Labour and Equipment- Skilled individual and costly equipment are needed

Soilless culture can help accurately control the root environment, improving production and quality (Table 1).

1.1.1. Soilless methods for producing potato mini tubers

Utilizing a technique known as clonal multiplication, which involves repeatedly propagating a sample free of diseases, is the traditional approach to producing mini tubers (also known as pre-basic seed potatoes). Unfortunately, this method of producing potato seeds is time-consuming, costly, and ineffective at preventing or reducing the development of diseases in later generations [17]. Micropropagation with *in vitro* multiplication, either through plantlet regeneration or micro tuber formation, is a superior substitute to clonal multiplication [18,19]. Stem cuttings, tissue culture, and—more recently—hydroponics are used in micropropagation. This enables year-round production of pathogen-free micro tubers in large quantities. Similarly, mini tubers are produced in a controlled environment with the help of soilless substrates, beds, containers, and nutrient solutions (hydroponics). Fig. 1 contrasts the various mini tuber seed production processes.

1.2. Hydroponics systems: types and operational mode

Hydroponics is a soilless agri-production system widely suitable for the cultivation of greenhouse crops. Hydroponics is one of the rapidly growing fields in agriculture and could be the alternate choice for sustainable agriculture. The world's population is growing faster than ever before, and this has led to the development of hydroponics, a potential method of growing vegetables without soil in cities. Controlled conditions, nutrient substrate and solid support pave the way for the development of hydroponics systems across the world, even in agro-climatic zones.

Commercial firms have recently cantered their efforts on hydroponics, which has risen fivefold in the last decade and has a global market value of up to $8 billion US dollars [20]. According to estimates, the global hydroponics sector is predicted to reach $17.9 billion by 2026 [21]. Environmental parameters such as dissolved oxygen, nutrient concentration, pH, and temperature typically affect the growth of hydroponic culturing plants; hence, sensors are necessary to monitor real-time measurements. Electrical conductivity sensors may be used to monitor nutrient concentrations because an increase in ionized nutrient content increases electric current [22]. Numerous crops have been produced via the hydroponic system in developed countries to fulfil customer demands. Researchers are concentrating their efforts on whole-plant potato physiology to optimize massive hydroponic systems used for commercial mini-tuber production, easing the gathering of physiological and anatomical samples for study.

Hydroponic systems may be closed or open depending on the growth medium used and the mechanism of nutrient circulation. Closed hydroponic systems do not need a growth medium. However, nutrient imbalances may occur in this system as time progresses if not maintained appropriately [23]. Thus, hydroponic nutrient solutions must be examined regularly, which makes them challenging to manage due to the varying mineral components. Specifically, in potato cultivation, plants absorb significant potassium (K) amount from the nutrient solution, resulting in a disproportion in the solution's potassium content [24]. In contrast, open systems continually recycle, monitor, and adjust nutrient concentrations.

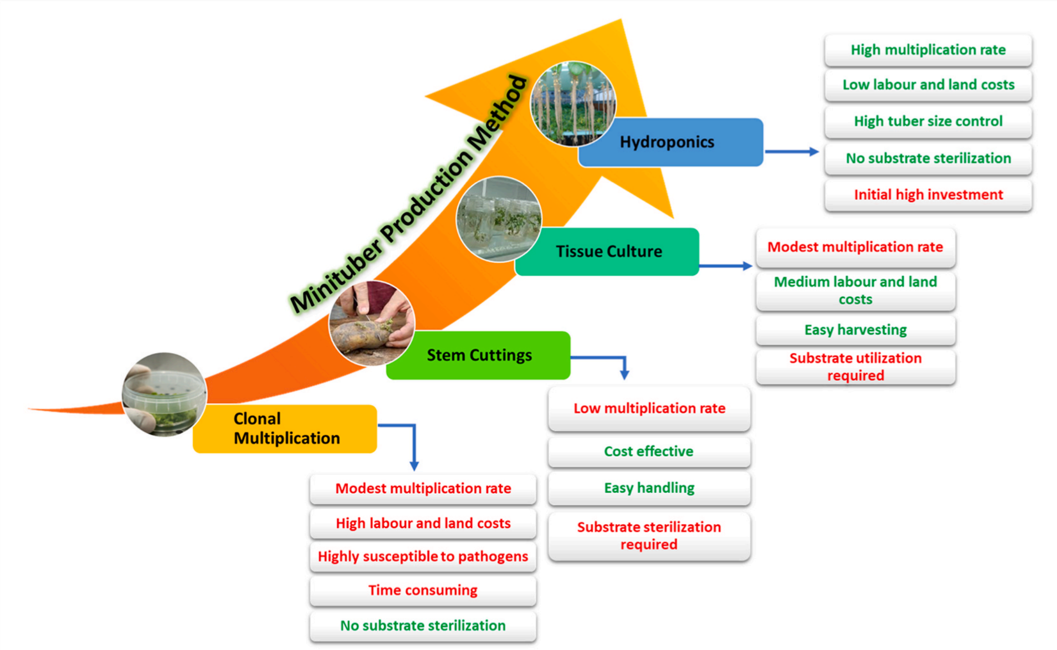

Fig. 1. Comparative analysis of various mini tuber seed production processes
Red font represents undesirable characteristics, whilst green font suggests favorable characteristics.

Multiple types of hydroponic systems vary in the pattern of their water/nutrition supply, among which Deep Water Culture, Wick System, Ebb and Flow (or Flood and Drain), Nutrient Film Technique (NFT), and Drip System are the most popular hydroponics systems (Fig. 2). Aeroponics is a more sophisticated hydroponic technique described later in this review. Table 2 comprises of the studies on potato mini-tuber cultivation using different hydroponic cultivation techniques.

1.2.1. *Wick system hydroponics*

For indoor hydroponics, the wick method is the most straightforward. The system is passive, and since it lacks a water pump, it is regarded as a self-feeding system (Fig. 2a) [36]. With the aid of a wick (usually nylon), the nutrient solution from the reservoir is transported into the growth media via capillary action. Wick hydroponics was used by Kim et al. [25] to examine how the number of wicks affected seed potato development and yield. The investigation's primary objective was to compare the growth of two types of wicks i.e., horizontal and vertical and also to determine the optimum wick number best for producing 'Dejima' seed potatoes (*Solanum*

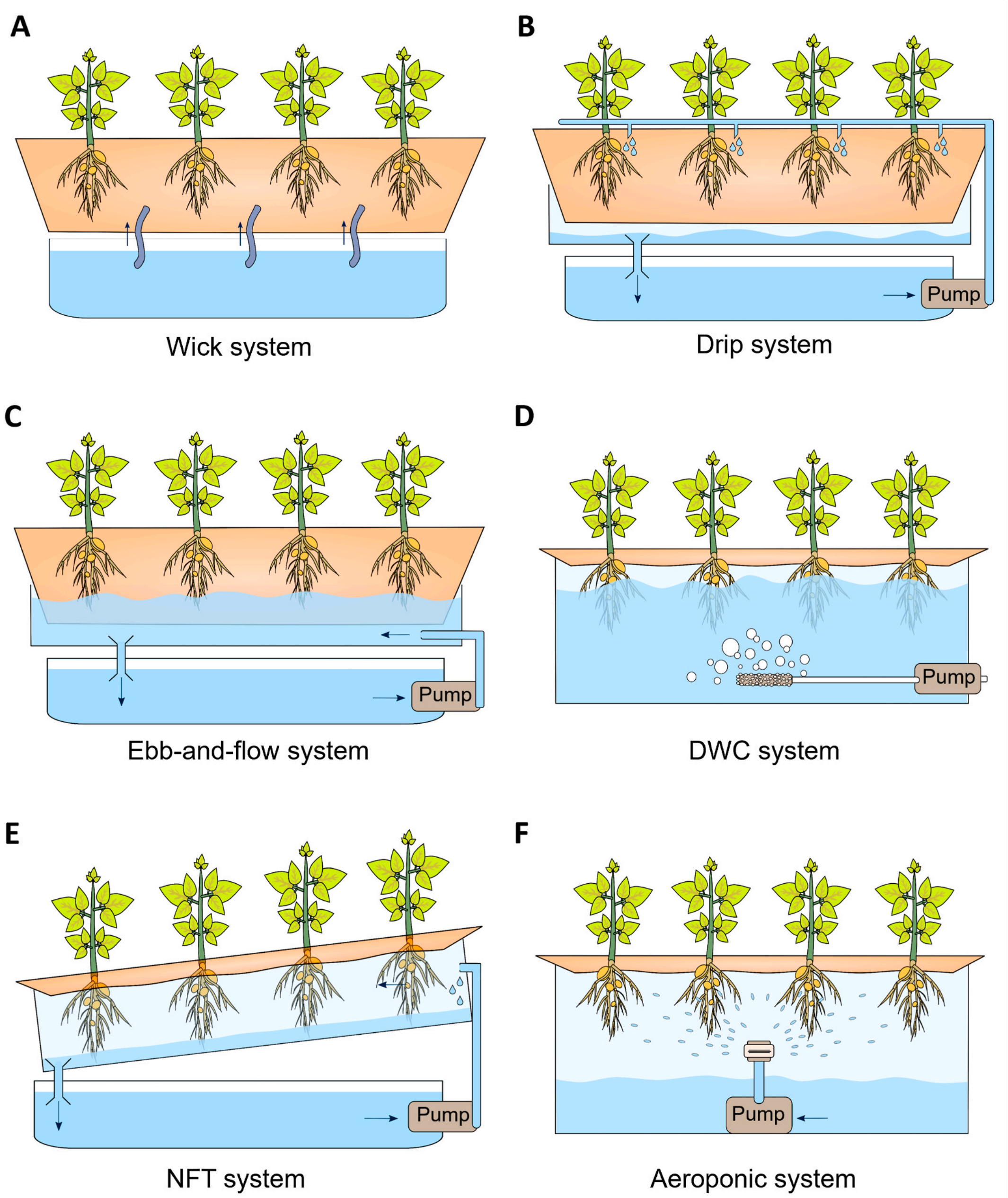

Fig. 2. Types of hydroponic systems (2a:Wick system, 2b: Drip system, 2c: Ebb-and-flow system, 2d: Deep water cultivation (DWC) system, 2e: Nutrient film technique (NFT) system, 2f: Aeroponic system).

Table 2
Studies on potato mini-tuber cultivation using different hydroponic cultivation techniques.

Hydroponic Technique	Cultivars	System specific condition	Harvesting time (days)	Number of minitubers/ plants	Tuber fresh weight (g)	Remarks	Reference
Wick system	Dejima	8 horizontal wicks	92	8.71	38.5	Horizontal wicks were observed showing better seed potato growth than vertical wick	[25]
Wick system	Dejima	8 wick/Multicote treatment (100 g/box)	90	3.25	38.2	–	[26]
Drip system	Spunta, lady rosetta and Hermes	–	∼107	7	20	Aeroponic system provided higher productivity and also less cost of tuber production per meter square	[27]
Aeroponic	Spunta, lady rosetta and Hermes	–	∼107	18	25		
Deep-water cultivation	Atlantic	–	90	63.8	222 g/plant	Deep-water culture was observed producing the highest number of small tubers compared to the aeroponic and hydroaeroponic system	[28]
	Superior	–	90	–	197 g/plant		
Nutrient Film Technique	Monalisa	Single harvest	90	18.98	25.07	Number of tuber/plant were observed to be 147% higher in NFT system as compared to bed and pot systems.	[29]
Nutrient Film Technique	Castrum	–	120	7.5	–	NFT system had a high number of tuber number and tuber weight per plant	[30]
Aeroponics	Hermes	25 plants/m^2 plant density	135 days with multiple harvests involved	22.7	3–8	The aeroponics system produced two to five times more tubers per plant than the conventional system.	[14]
	Sante			25.7	3–8		
Aeroponic	Agata & Monalisa	Observations of both cultivars were taken as average in a hydroponic system	∼120 days with multiple harvests involved	49.3	6.8	Aeroponic system exhibited the best results and Monalisa cultivar showed higher fresh mass and diameter than the Agata cultivar	[31]
Nutrient Film Technique	Agata & Monalisa	Observations of both cultivars were taken as average in a hydroponic system	∼120 days with multiple harvests involved	39.5	6.2		
Aeroponic	Agata	–	95 days	46.9	–	Aeroponic system exhibited the best results	[32]
Nutrient Fim Technique	Agata	–	95 days	34.8	–		
Aeroponic	Agata	2.2 dS•m^{-1} electrical conductivity of the nutrient solution	95 days	33		Planting density and electrical conductivity of the solution showed significant effects on seed potato production	[33]
	Asterix	2.1 dS•m^{-1} electrical conductivity of the nutrient solution	95 days	20.4			
Aeroponic	Desiree	–	49	15.55	5.32	Aeroponic system produced 4.08 and 1.29 times higher mini-tubers than the substrate and combination system	[34]
	Kenebbec	–	49	11.99	7.61		
	Agria	–	49	10.70	8.97		
	Cleopatra	–	49	10.52	6.36		
	Sinora	–	49	10.66	4.83		
Aeroponic	Kachpot1	24 plantlet/m^2 plant density	∼150	22	–	Aeroponic production was observed producing 8.5 times the mini-tubers than the conventional system	[35]
	Victoria	24 plantlet/m^2 plant density	∼150	23.2	–		
	Uganda11	24 plantlet/m^2 plant density	∼150	41.5	–		

tuberosum L.). The growing medium used in that study was a 1:2 perlite and peat moss mixture. In a prior optimization of growth medium in wick system, Kim et al. [37] found the perlite and peatmoss system to be the most suitable. Two to ten wicks were placed horizontally via holes in the polystyrene box's base and six wicks were placed vertically. However, six horizontal wick generated more tubers per plant than the six vertical ones, and the average tuber weight dropped. But, by increasing the wick count to eight, the average tuber weight increased. The results suggested that eight wick per box was optimum for the production of 'Dejima' seed potatoes. In a study conducted by Kang and Han [26], 'Dejima' seed potatoes were grown in a wick hydroponic system, where the effect of nutrient solution, NPK fertilizer and control released fertilizers such as osmocote, multicote and Magamp K was tested on the production of seed potato. The number of tubers per plant was observed to be the highest (3.25 tubers/plant) in Multicote (100 g/box) treatment, whereas the highest average tuber (38.4 g/tuber) was observed in the nutrient solution treated plants. In a wick hydroponic system, the yield of potato plug seedlings was studied by Kang [38]. Commercial growing mixtures such as *Jeju scoria* + cocopeat, *Jeju scoria* + perlite, perlite + cocopeat (1:1 or 1:2, v/v), perlite + peat moss, and perlite + peat moss were used to make nine different types of growing media. Among the media studied, the findings indicated that perlite + peat moss (1:2) and *Jeju scoria* + peat moss (1:2) were the most suitable for seed tuber development and growth using a wick culture technique.

The prime factors for considering this hydroponics approach include operation without the involvement of pumps, electricity, or aerators with low maintenance. Furthermore, because it doesn't rely on electricity for the transportation of nutrients, it can be used in places where electricity is a major concern [39]. The Wick system is appropriate for herbs, small plants and spices [23].

Even though the wick system is simple and affordable, nutrient recycling is impossible since water is transported to the plants by capillary action, either by open or closed circulation [39]. Limited oxygen access, slower growth rate, and easily prone to algal growth are the significant limitations to using this system in a wide range of commercial applications. Moreover, the system is suitable only for small-scale crops with extensive periods that cannot be cultivated [20]. Similarly, many plants may consume the nutrient solution before replenishing it with the wicks. So, cultivating plants that require a high amount of water is tedious [23].

1.2.2. Drip system hydroponics

Drip system hydroponics uses pipes, hoses, and a growing media to provide regular nutrition and watering (Fig. 2b). This technology is like drip irrigation in soil gardening, gaining popularity and becoming the industry standard in hot and dry locations. Long pipes and hoses irrigate crops, save water, and decrease evaporation. Using an automated timer, a pump distributes water or fertilizer solution to individual plants or pots [40]. Presently, Big Data and IoT (Internet of Things) are employed in smart farming to modernize conventional agricultural farming to conserve nutrients and water. Sensors could help in monitoring the parameters such as temperature and soil moisture. Kumari [41] examined the effect of drip irrigation on potato (*Solanum tuberosum* L.) water consumption efficiency, leaf area maximization, and yield. That research evaluated the efficacy of a tangible way of repeated water delivery by the drip irrigation system. Frequent watering with water ensured efficient water usage and minimized system water loss. Leaf area and yield were considerably more remarkable in this system. In a recent conducted by Bakr et al. [27], a comparison between drip hydroponic and aeroponic and optimization of water productivity was done in potato mini-tuber production. The aeroponic system was observed to be better in yield productivity of mini-tubers than the drip cultivation. A drip hydroponic system designed by Kusnierek et al. [3] resulted in the production of ∼300% higher potato tuber than the conventional system. The mineral composition of hydroponically grown potatoes was found to be similar to the ones grown in the field and their finding also suggested the potential of drip hydroponics in biofortification of food crops.

The significant advantage of this method is less water consumption. A drip system can survive equipment failures and short-term power. Moisture levels can be easily controlled in a drip system. Enough oxygen transfer favors crop cultivation in soil and hydroponic systems [39]. Recirculation of excess nutrients is also possible in this system. Crops like cucumbers grow very well in the drip irrigation system. Similarly, superior tomatoes and peppers typically grow higher in the drip system when compared to other systems because they provide enough stability [42]. The major limitation of the drip system includes being easily prone to algal growth and clogging, so regular cleaning is mandatory.

1.2.3. Ebb and flow (or flood and drain) hydroponics system

It is considered a more popular system in which plants are kept in large grow beds, usually filled with growing medium. A pump generally coupled to a timer is used to accomplish this (Fig. 2c). The timer regulates the flow of nutrient solutions in the environment. If the timer puts the pump on, it allows the nutrient solution in the growth tray, and if it shuts off, it pumps the nutrient solution back into the reservoir. In this approach, one must rinse roots often for brief intervals. So, it is unnecessary to endure extended exposure to the water, and they may remain wet, ensuring they can breathe. Nevertheless, continual observation is necessary to monitor water flow to the system. Son et al. [43] analyzed the existing sub-irrigation systems for potted plants. Their study compared a diverse experimental setup, such as a wick system with the nutrient-flow and nutrient-stagnant wick system, with the Ebb and flow method. While the water content of the medium under the nutrient-stagnant system gradually climbed to over 40% without fluctuation, the water content under the nutrient-flow and ebb & flow systems showed fluctuations from 30 to 40% and from 50 to 60% (by volume), respectively. The evaporation rate was 50–70 % less in the nutrient wick when compared with other systems. No studies in literature were observed where ebb and flow hydroponic system was used for potato seed production.

The ebb and flow system is affordable, enhances nutrient recirculation, and requires low maintenance. It is the preferred choice for growing celery and melons. The primary limitations include the formation of root rot and crop loss due to technical failure. In addition, it is easily prone to algal growth. In order to overcome this, the system can be improved, and the filtration unit can be incorporated [44].

1.2.4. *Deep water cultivation (DWC) hydroponics system*

DWC is a modified hydroponic system with an air stone, reservoir, air pump, tubing, and floating platform [45]. This system includes a tank (generally called a grow tank) containing the nutrient solution and a pump to supply oxygen to the roots (Fig. 2d). In the presence of an air pump, more plants can be cultivated in a single grow tank. Plant roots usually float in nutritional solutions for water, oxygen, and nutrients [46]. Oxygen, pH, and fertilizer levels must be monitored to optimize salinity [47].

Fong and Ulrich [48] first conducted a deep water cultivation study on potato cultivation. In their study, seedlings were collected from certified white rose tubers and subjected to drying overnight before plantation 1 inch deep in flats containing alveolate. It was given a nutritional solution without potassium (K). Seedlings of uniform size were selected and transplanted outside in five-gallon pots containing 20 L of solution. The plant development was somewhat reduced in the potassium-deficient feed media. Meanwhile, adding potassium to the nutrition solution increased plant growth. The water culture approach proved effectiveness in studying potassium shortage symptoms in potato plants.

Chang et al. [28] performed a comparison of potato seed tubers production in three different hydroponic systems, i.e. aeroponic (discussed later), aerohydroponic and deep-water culture. The aerohydroponic system was designed by maintaining the contact of the root to the nutrient solution in lower bed part while spraying the upper root part intermittently. The deep-water cultivation system showed a delayed tuberization in comparison to aeroponic and aerohydroponic cultivation. The deep water culture was observed producing the highest number of tubers but the total tuber weight/plant was least among the three. In their conclusion, it was stated that small tubers (1–5 g) for plant propagation can be produced using the deep water culture.

The system is reliable and cheap, and an air pump uninterruptedly supplies oxygen to the crop root zone. A simple experimental setup in plastic boxes, glass basins, ice boxes, and fish ponds is enough for crop cultivation. Deep water cultivation is best suited for producing cherry tomatoes, cucumber, Chinese cabbage, lettuce, spinach, and radish [49]. However, crop cultivation using this method has not been commercialized extensively because of a few limitations, such as contact area between air and water and oxygen transfer efficiency [50]. Moreover, a few parameters, such as concentration of the nutrients and oxygen, salinity, and pH, must be critically monitored to evade algal and mold growth in the reservoir [23].

1.2.5. *Nutrient film technique (NFT) hydroponics system*

NFT technique requires only a thin layer of solution at the bottom of a deep tank (a “film” in actuality; Fig. 2e). Consequently, the lower half of the roots will receive food and water, while the upper half will be allowed to breathe [51]. This technique is used when plants respond by producing roots that reach the film and then extend horizontally when it is initially produced. This system exposes the root surface to the air during nutrient solution circulation. The pump is generally in mode to monitor the nutrient solution constantly [47].

In a study conducted by Corrêa et al. [29], the researchers compared the potato seed tuber production of Monalisa and Agata cultivars in NFT with traditional beds and pots methods. In terms of tubers/plant number in single and staggered harvest, the NFT system performed better statistically. In a single harvest the number of tubers in hydroponically grown seed potato plants was 147% higher than the bed and pot systems. Even in the staggered harvest, an increase of 286% in tubers was observed in the hydroponic plants as compared to the ones grown in beds NFT was used to examine the yield of potatoes [52]. “Denali and Norland” potato cultivars were grown in polyvinyl chloride trays using continuous flow nutrition film. Nutrient solution pH was automatically maintained, and water was manually added daily, while nutrients were supplied twice a week. Each tray had one or two 112-day plants. As a result, Denali plant trays produced 2850 and 2800 g of fresh tuber weight, respectively. Tican [30] compared mini-tuber development in two industrial substrates (perlite and expanded clay) and two hydroponic systems (wilma and NFT). The NFT was observed having positive results in terms of minituberization, mini-tuber number and weight. Medeiros et al. [53] conducted an experimental study using different NFT systems to produce seed tubers and highlighted the significant advantages and drawbacks. The first method dealt with the aid of deep channels of 6 cm, roofing with asbestos made of polyethylene membrane, spaced each other by 18 cm, and placed on a wooden platform with a slope of 4%. The second method was the same as the previous method, with asbestos roofing overlapped with PVC channels. These two strategies were tested for the potato growth of pre-basic seeds. The study revealed that a greater multiplication rate was achieved by this technique when compared with other methods.

The NFT hydroponic system enhances the recirculation of excess solution of nutrients and aids in the proper oxygen supply. Also, it is economical since it can be organized in multilevel, matrix farming, and vertical orientation. In addition, it minimizes land usage, labor and fertilizers compared to other systems. Water consumption is also very minimal, and it is climate resistant. It is most suitable for smaller and fast-growing plants such as lettuce [54] and is the most preferred technique for the cultivation of tomatoes. Blueberries, strawberries, and melons can be cultivated in NFT since it provides an ideal environment. Herbal plants like chives prone to drought stress can be cultivated better in NFT. Despite the fact that NFT is one of the most widely used hydroponics techniques, a lot of studies are concerned that exposing tuber roots to an excessive amount of salt from the nutrition may harm their periderm tissue. Thus, aeroponics has been promoted and applied in an effort to boost productivity.

2. Aeroponics: a modified version of hydroponics to grow mini tubers

Plants produced by aeroponics thrive in an air or thick fog environment (Fig. 2f). It involves spraying a nutrient-rich water solution onto the plant’s hanging roots [55]. Lower stems occur in a closed or semi-closed environment using a high-pressure sprayer with a micro inject nozzle and an electronic timer [56]. It provides highly oxygenated nutrients to the plants. However, it is essential to customize the misting cycles for plants since their roots are exposed to the air and will dry rapidly. In addition, outside temperatures can easily affect the mist and make the system more challenging to operate in frigid conditions [57]. Several countries (including South

Korea, New Zealand, China, Africa, Spain, and Latin America) have used aeroponics to grow mass amounts of potato mini-tubers. Aeroponics started with complicated equipment and relatively low yields, but by 2006, the International Potato Center (CIP) had improved the yields and made aeroponics work in developing countries [58]. Aeroponics is the future of soil-free agriculture. Growing tubers and rhizomes in an aeroponic system have the potential to be more profitable than growing them in a hydroponic or soil system. Mini-tubers cultivated aeroponically are also harvested differently than those grown conventionally. The fundamental distinction is in the sequential harvests of aeroponic plants. There is only one final harvest in the conventional system, while depending on the cultivar, up to ten or more harvests are possible using aeroponics.

A competent aeroponics system may produce 100 tubers per plant [59,60]. Aeroponics is the most popular hydroponics system in the world. Its application in tropical regions such as Brazil has attracted much attention since it improved the production of virus-free seed potatoes [33]. This approach is the most popular alternative for potato seed growing in the highlands; nevertheless, in the lowlands, implementation is one of the most significant restrictions due to high temperature, which affects the commencement and growth of the tuber. Sumarni et al. [61] conducted a complex investigation on the cultivation of potatoes utilizing aeroponics and the root zone cooling method in the lowlands. Approximately 579 tubers per square meter and a height of 115 m above sea level were recorded at 10 °C using this method [62]. In a study by Brocic et al. [34], five virus-free potato cultivars were grown using a substrate system, an aeroponic system, and a combination of the two systems. Mini tubers output by plants cultivated in an aeroponic system was 4.08 times higher than the substrate system and 1.29 times higher than the combination system, with the 16–19 °C optimum for initial growth and 18–22 °C for filling. Çalışkan et al. [14] in their evaluation of mini tuber production of three different cultivars in conventional and aeroponic systems found the number of tubers per plant higher in aeroponic cultivation as compared The plant density was observed to be playing a major role in the tuber production, where with increasing plant density in aeroponic system, the number of tubers/plant was observed to reducing. The 200 plants/m^2 plant density showed a mean tuber number in a range of 9.6–16.8 in three cultivars in two different cycles of plant growth, whereas 25–50 plants/m^2 density showed 14.0–25.7 mean tuber number.

In a comparison between three hydroponic systems, i.e., aeroponic, deep flow technique and NFT, for the production of potato

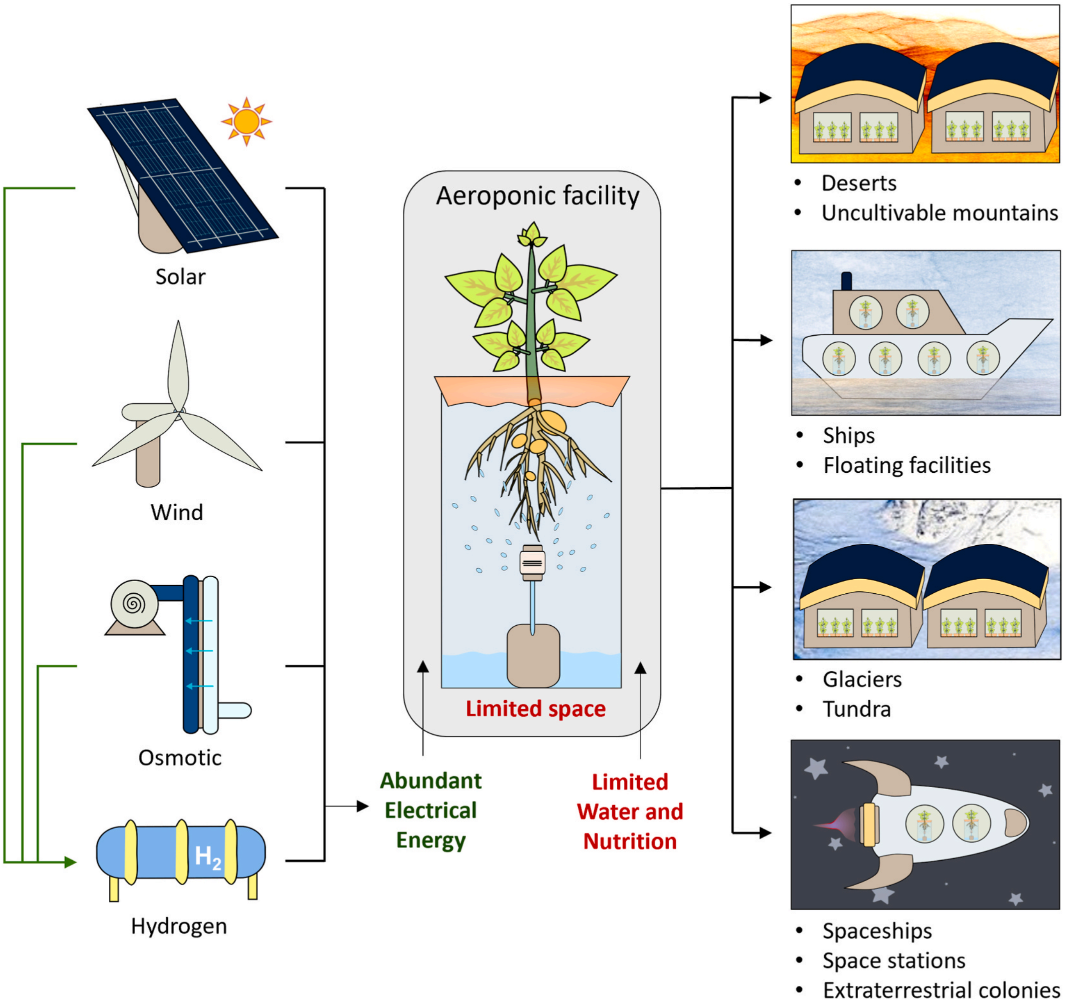

Fig. 3. Feasibility of aeroponics farming to support potato cultivation irrespective of agroecosystem.

mini-tubers by Factor et al. [31], the aeroponic system was observed to be producing the highest mini-tubers per plant (49.3/plant) as compared to the deep flow technique (41.6/plant) and NFT (39.5/plant). However, the hydroponic system did not appear to have any effect on the longitudinal diameters or fresh weights of the tubers. In a further study by Factor et al. [32], the same observations were made where the aeroponic system was observed showing best results among the three types of hydroponic systems.

In Uganda, Kakuhenzire et al. [35] found that aeroponics increased potato mini tuber output by 8.5 times than the conventional cultivation. Small tubers per plant determined multiplication rates. Low plantlet density resulted in high mini-tuber output. In another study, Calori et al. [33] studied the role of electrical conductivity (EC) on nutrient intake and growth of Agata and Asterix potato varieties. Potato seedlings were seeded in phenolic foam and then aeroponically. To follow tuber initiations, air temperature, growth cycle, shoot development, and mini tuber output of both cultivars during different seasons, electrical conductivities (1, 2, 3, and 4 dS m^{-1}) and planting densities (25, 44, 66, and 100 plants m^{-2}) were evaluated. Both cultivars had optimal ECs below 2.1 and 1.7 dS m^{-1}, respectively. The selected cultivars responded economically at 100 plants m^{-2}. Several African nations also employed aeroponics to develop potato micro tubers [63]. It produces more flavonoids, phenolics, and antioxidants than soil cultivation and minimizes the amount of water potato plants need and ensures they get enough oxygen [64,65].

Aeroponics farming requires less water and no soil, so it is a prudent option for promoting mini tuber production in challenging potato cultivation environments, such as deserts, cold steep terrains, and coastal regions. Mini potato tubers grown in an aeroponic system can either be transported to an adjacent open field, or the technique can be utilized for crop production in hostile environments. Aeroponics systems don't need fertile land to be installed, and closer plant spacing is possible. This has led to the emergence of intriguing ideas about growing crops on space stations, sailing ships, and extraterrestrial colonies (Fig. 3). Recently, Klarin et al. [66] presented an intriguing design for a marine aeroponic infrastructure that can enable the production of mini tubers on huge ships utilizing solar and wind power. Aeroponics-based crop production in interplanetary colonies or space stations may soon be the subject of enthralling research projects [67]. However, the technology is still in its infancy and has room for development. The system still requires a good environment and appropriate techniques, and hence more elaborative research is warranted. For example:

- Optimizing nutrition solutions for various potato cultivars.
- Identifying the local nutrient source to reduce input costs.
- Cost-benefit analysis to determine the practicality of aeroponics systems for the generation of mini tubers in developing nations

Nevertheless, aeroponics can become a technology that contributes to global food security with adequate planning, research funding, and the incorporation of advancements (described in the following section).

2.1. *Technological advancements in hydroponics*

Industrialization is changing the face of agricultural advancements just as it does to the rest of society. As a result of hydroponics technology, it is possible to produce food crops in harsh environments such as hilly areas too high to cultivate, concrete school playgrounds, and arctic settlements. Beyond staple crops and vegetables, hydroponics may also produce specialty crops like salad leaves, spices, and ornamental plants in urban locations where land prices have replaced conventional farming [68]. Artificial lighting, agricultural plastics, and pest and disease-resistant cultivars will enhance crop yields and cut production unit costs. Rahman et al. [69] examined the effects of artificial LED light on potato pre-basic seed tuber production in their study. In their observations, the red + far red light combination was seen to enhance the overall potato plant growth. Different artificial light combinations positively affected the number of seed tubers, fresh tuber weight, photosynthetic pigment accumulation, carbohydrate and sucrose content. Different studies have confirmed the positive influence of using artificial light in hydroponic and aeroponic potato mini-tuber production, which can be harnessed for better yield and cost reduction by optimization of these systems [69–72]. Waste heat from industry and power plants is now used in hydroponic greenhouses as an emerging trend to enhance energy efficiency [73].

Since the hydroponics system utilizes only water and nutrient solution without the involvement of soil, any failure or problem in the nutrient distribution, water pump, or nozzle clogging will lead to rapid death of the growing plants. Special attention is required to ensure real-time monitoring of the growth and development of the plant. As described below, hydroponic systems may benefit from including a few new features (Fig. 3).

2.1.1. *Sensors and artificial intelligence (AI) for real-time monitoring*

Precision agriculture, a newer concept known as smart agriculture, uses cyber-physical techniques to combine information and communication technology (ICT) in all phases of the farm management cycle [74]. Sensors and data analysis tools can be used throughout the culture for real-time plant growth monitoring. Robots using position-based visual feedback could improve smart hydroponic farming [75]. Smart hydroponics might help find the best way to grow a plant by combining hardware setup with a software tool replicating the plant's growth trajectory [56]. Nutrient and light sensors are now used in artificial intelligence (AI)-assisted hydroponics [76]. One can gather information via sensors installed in the gadget to gather data—for example, shifts in temperature, humidity, and light intensity. When the AI computer visualizes the developing plant's colors, it identifies the parameters to be executed, like providing nutrients to the soil based on the specific colors upon recognition.

The parameters of hydroponic solutions may be self-calibrated and managed using machine-learning algorithms based on sensor data [77]. The AI system directly delivers the nutrient solution, water, and light to plant roots using sensors. However, as sensor technology develops, more data is being created, making it challenging to utilize them correctly.

2.1.2. Nanoparticles

Nanoparticles (NPs) are used in agriculture to increase nutrient management and crop production. Due to their large surface area and relevant reactivity, NPs offer the plant readily accessible nutrients by enhancing the soluble and available forms of nutrients [78]. Precipitation and insolubilization processes are often related to bulk fertilizers. The use of nanoparticles as a delivery mechanism promises to be significantly more efficient than current approaches [79–81]. Nanoparticles have been shown to alter critical responses in plants, such as germination, seedling vigor, root development, and photosynthesis [82,83]. Additionally, several studies revealed that nanoparticles might provide plants with a better defense against oxidative stress since these particles can imitate antioxidant enzymes, viz., superoxide dismutase, catalase, and peroxidase [84]. It has been shown that nanoparticles can be used to reduce the impacts of temperature, salt, and drought stress on plants by enhancing their tolerance to these stresses [85].

Benefits arising from this technology are relevant not only for soil but also for soilless systems. Nanoparticles were utilized in hydroponics systems to accelerate the development of various plants such as spinach and tomato [86]. The introduction of nanoparticles produced promising plant growth and disease resistance outcomes. In a study conducted by Homaee and Ehsanpour [87], the effects of silver nanoparticles (AgNPs) or silver nitrate ($AgNO_3$) on *in vitro* culture of potato plants were investigated. It was observed that growth parameters, such as leaf area, root length, shoot dry weight, and root dry weight, increased in the plants treated with $AgNO_3$ and AgNPs. Plants treated with $AgNO_3$ or AgNPs at two mg/L had significantly more chlorophyll than control plants. All indicators exhibited substantial growth and pigment differences treated with nanoparticles except for shoot length.

Since nanotechnology is still in its infancy, close attention needs to be paid to the toxicity and trophic transmission of nanoparticles in our surroundings. To wrap things up on a bright note, recent studies have found that potatoes have far more nano Iron, Calcium, and Zinc than they did a few years ago. This can result in lower rates of disorders such as iron deficiency anemia in less economically developed nations. Recent interest has been focused on Engineered Nanoparticles because of their diminutive size [88]. Silicon (Si) increased crop output when foliar-sprayed as nanoparticles under varied conditions, including salinity [89], toxic heavy metals [90], and drought [91]. In a study by Saadian et al. [92], nano and ionized Si derived from sodium silicate were examined at concentrations ranging from 0.8 to 3.2 mmol Si L^{-1}. In that investigation, 3.2 mmol Si L^{-1} was determined to be the ideal concentration. In comparison with treatments employing ionized Si, nanoparticle Si yielded superior results. The application significantly increased photosynthetic and biochemical indices. Additionally, it improved water use efficiency.

2.1.3. Plant growth-promoting rhizobacteria (PGPR)

PGPR are bacteria that may enter plant roots after being injected onto the seed and stimulate plant development. They inhabit rhizospheres and rhizoplanes in nature. PGPR enhance the bioavailability of mineral nutrients in the rhizosphere by stimulating a variety of processes such as atmospheric N_2 fixation, P solubilization, and siderophores production for Fe^{3+} chelation [93–96]. It can act as a biocontrol agent and a nutrient-fixing organism. Therefore, adapting such microbes to a hydroponics system can potentially boost productivity and reduce the cost of nutrients in the case of potato mini tuber.

Several beneficiary microorganisms were reported for the plant's growth in the hydroponics system. Results revealed that significant differences occur upon treatments with plant growth-promoting bacteria. Table 3 highlights the beneficiary microorganisms used for plant growth in a hydroponic system.

3. Conclusion and perspective

Mini tuber production is a standard technique for propagating or acclimating *in vitro* material before its application in the field. Traditional methods (soil-based) of cultivation need more heightened monitoring and micromanagement. Low mini tuber multiplication rates are a further disadvantage of this production method. In recent years, hydroponic systems have emerged as incredibly successful approaches to raising potato mini tubers. Very high rates of tuber multiplication, no concerns of tuber contamination by soil pathogens, and reduced frequency of physiological disorders are only a few of the many benefits connected with hydroponics in producing mini tubers. The nutrient film technique, deep flow cultivation, and recently, aeroponics are being exploited for growing potatoes. Although aeroponics resulted in a significant increase in tuber yield relative to other methods now in use, additional work is required to refine the technology and promote its widespread adoption. It includes the development of protocols for location-specific cultivars, the examination of correlations between production components, and the standardization of plant densities, harvest

Table 3
Beneficial microorganisms and the host plant interaction in a hydroponics system.

Microorganism		Host Plant	References
Genus	Species		
Bacillus	*cereus, amyloliquefacians, thuringiensis, subtilis*	Carnation, bean, chickpea, lettuce, peppers, cucumber, potato, tomato, and radish	[97–102]
Pseudomonas	*aureofaciens, aeruginosa, corrugate, chlororaphis, fulva, fluorescens, putida, oligandrum, syringae marginalis, plecoglossicida,*	Chrysanthemum, tomato carrot, lettuce, cucumber, pepper,	[103–110]
Streptomyces	*griseoviridis*	Tomato and cucumber	[111,112]
Enterobacter	*aerogenes*	Cucumber	[113]
Trichoderma	*atroviride, virens, asperellum, harzianum.*	Cotton, bean, maize, cucumber, and rice	[114,115]
Gliocladium	*catenulatum*	Tomato and cucumber	[116]

frequency, and harvest intervals.

To produce mini tubers via hydroponics systems, periodic monitoring of the pH and nutrient levels is necessary. Even though a variety of methods aid in the production of mini tubers, more sophisticated and cutting-edge methods to monitor potato crops in real-time could be used. Nowadays, most people prefer it, but few farmers have access to such technology. Furthermore, the state of the art in hydroponics may undergo significant changes as a result of PGPR and nanotechnology for improved nutrient absorption by mini tubers, making it more sophisticated and sustainable. The whole concept of farming is evolving. It can be hypothesized that these technological advancements in aeroponics and hydroponics will present countless opportunities to increase food security, particularly important for farmers who usually farm less than 2 ha of land. Developing such sophisticated soil-less farming has, therefore, allowed for a wide variety of research, raising expectations that can help nourishing the next generations. It should be no surprise that the hydroponics/aeroponic system is the most promising method for mass-producing mini tubers in any environment that humans can access, i.e., land, water, or space.

CRediT authorship contribution statement

Sasireka Rajendran: Writing – original draft, Conceptualization. **Tenzing Domalachenpa:** Writing – original draft, Conceptualization. **Himanshu Arora:** Writing – review & editing. **Pai Li:** Visualization, Software. **Abhishek Sharma:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Gaurav Rajauria:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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