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Protected Agriculture, Precision Agriculture, and Vertical Farming

Brief Reviews of Issues in the Literature Focusing on the Developing Region in Asia

Hiroyuki Takeshima

Pramod Kumar Joshi

Development Strategy and Governance Division
South Asia Regional Office

INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE

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AUTHORS

Hiroyuki Takeshima (H.takeshima@cgiar.org) is a Senior Research Fellow in the Development Strategy and Governance Division of the International Food Policy Research Institute (IFPRI).

Pramod Kumar Joshi (p.joshi@cgiar.org) is the Director of IFPRI's South Asia Regional Office (SAR).

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Abstract

The frontiers of technologies have been constantly expanded in many industries around the world, including the agricultural sector. Among many "frontier technologies" in agriculture, are *protected agriculture*, *precision agriculture*, and *vertical farming*, all of which depart substantially from many conventional agricultural production methods. It is not yet clear how these technologies can become adoptable in developing countries, including, for example, South Asian countries like India. This paper briefly reviews the issues associated with these three types of frontier technologies. We do so by systematically checking the academic articles listed in Google Scholar, which primarily focus on these technologies in developing countries in Asia. Where appropriate, a few widely-cited overview articles for each technology were also reviewed. The findings generally reveal where performances of these technologies can be raised potentially, based on the general trends in the literature. Where evidence is rich, some generalizable economic insights about these technologies are provided. For protected agriculture, recent research has focused significantly on various features of protective structures (tunnel heights, covering materials, shading structures, frames and sizes) indicating that there are potentials for adaptive research on such structures to raise the productivity of protected agriculture. The research on protected agriculture also focuses on types of climate parameters controlled, and energy structures, among others. For precision agriculture, recent research has focused on the spatial variability of production environments, development of efficient and suitable data management systems, efficiency of various types of image analyses and optical sensing, efficiency of sensors and related technologies, designs of precision agriculture equipment, optimal inputs and service uses, and their spatial allocations, potentials of unmanned aerial vehicles (UAVs) and nano-technologies. For vertical farming, research has often highlighted the variations in technologies based on out-door / indoor systems, ways to improve plants' access to light (natural or artificial), growing medium and nutrient / water supply, advanced features like electricity generation and integration of production space into an office / residential space, and water treatment. For India, issues listed above may be some of the key areas that the country can draw on from other more advanced countries in Asia, or can focus in its adaptive research to improve the relevance and applicability of these technologies to the country.

Keyword: Protected agriculture, Precision agriculture, Vertical farming, Developing countries

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1 Introduction

The frontiers of technologies have been constantly expanded in many industries around the world, including the agricultural sector. Among many "frontier technologies" in agriculture, are *protected agriculture*, *precision agriculture*, and *vertical farming*, all of which depart substantially from many conventional agricultural production methods. While the costs of adopting these technologies have remained high, continuous innovations have led to either the development of less sophisticated but more affordable technologies or systems, and / or the overall reductions in the technology costs in general.

As the potentials of applying these technologies become greater, albeit slowly, the body of related research has also continued to expand. It is, however, not yet clear how these technologies can become adoptable in developing countries, including, for example, South Asian countries like India. There is a need to identify and compile key issues that are associated with these technologies, and potentially relevant to these countries. In this paper, we aim to partly fill this gap, by briefly reviewing the key issues which may be relevant to these countries, associated with these technologies. While one of the ultimate goals would be to identify the key strategies to optimally promote the wider uses of these frontier technologies in the agricultural sector, that is a lengthy process. In this brief review, we primarily focus on summarizing and categorizing the issues that have drawn more attentions in the literature, mostly in developing Asia. Such information can help us understand where the research community including the private sector (in developing Asia and elsewhere) see greater potentials to improve the performance of these technologies, and to devise more intermediate versions of the technologies or systems that are less sophisticated and with limited functions but are affordable and still beneficial for the greater majority of users in low-income countries like India.

We do so through a systematic search of the literature archived in Google Scholar. For each of these technologies, we first search relevant studies using specific terms ("protected agriculture", "precision agriculture", "vertical farming", and their minor variants like "farming" instead of "agriculture"),[1] and compile them using *Publish or Perish* software, which is a free software that allows more systematic analyses of the references listed in Google Scholar website (Harzing 2007). In the case of relatively more widely adopted technologies like protected agriculture, this generally leads to 1,000 or more studies per year (particularly in recent years). We then filtered the studies by those that specifically included the names of the developing countries in Asia in the title. This is based on the assumption that those studies are likely to be most directly relevant to these frontier technologies and their applicability to developing Asian countries including India. While there are likely to be many other studies that are more indirectly relevant and still provide useful insights, it is assumed that covering the first set of studies can provide the majority of key insights that are directly relevant. There are also several widely-cited overview-type studies, which provide useful insights on the overall set of issues, and information of adoption trends in more developed countries. Where appropriate, these studies are also reviewed and relevant information is extracted.

This review is structured in the following way. Section 2 covers protected agriculture. Section 3 covers precision agriculture, while section 4 covers vertical farming. In each of section

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[1] For vertical farming, similar technologies like aquaponics and its variants are also considered. Aquaponics or hydroponics are production systems that combine fish farming with soil-less vegetable production in one recirculating system, in which nitrifying bacteria convert fish waste (ammonia) into plant food (nitrate). (Somerville et al. 2014).

2 through 4, we first provide some overview of the adoption trends of selected sub-types of technologies, and then describe the key issues and aspects that recent research has highlighted. For each section, we first describe the general trends of the use of each type of technologies around the world, and then describe key aspects of their technological and economic characteristics that are generally covered in the literature focusing on developing Asia.

2 Protected agriculture

Protected agriculture generally refers to the technologies that involve methods of plant coverage and climate control (Jensen and Malter 1995). Some of the most prominent examples of protected agriculture include mulches, row covers and green houses, among others. Good overviews of these technologies are provided in various studies, including Jensen and Malter (1995) which provides global review up to the mid-90s, and Castilla (2012) which focuses on greenhouses. Among the three frontier technologies reviewed in this paper, protected agriculture has included relatively more affordable versions of technologies (like mulches, low-cost greenhouses), and has been relatively more widely adopted.

2.1 Trends in the world – protected agriculture

The growth of protected agriculture has been highly uneven, regionally, as well as within countries. Common types of protected agriculture that have been covered in the literature include mulching, plastic greenhouses, as well as low tunnels.[2] Among greenhouses, the spread of glass houses has so far been considerably low compared to plastic greenhouses.

Globally, the areas under mulching and greenhouses are estimated to have increased multiple-folds between the late 1980s and 2010 (Table 1). Areas under mulching, and, greenhouses are estimated to have increased from about 3.5 million hectares (ha) to 10 ~ 20 million ha, and about 200,000 ha to 2 million ha, respectively.[3]

Table 1. Areas under different types of protected agriculture in 1987-89 and 2010, by regions around the world (1000 ha)

	Asia	Mediterranean	Rest of Europe	America	Others	Total
2010						
Mulching	9,870 ~ 20,000	402	65	265	15	10,617 ~ 20,000
Direct cover	22	16	39	13	15	105
Low tunnel	1,505	133	9	20	5	1,672
Greenhouse	1,630	201	45	25	4	1,905
1987-89		Europe				
Mulching (plastic)	3000 ~ 3329	158 ~ 210		180 ~ 200	8 ~ 10	3346 ~ 3749
Row cover (plastic tunnels)	165	80		10	10	265
Greenhouse (plastic)[a]	91 ~ 95	71 ~ 76		8 ~ 10	15 ~ 17	185 ~ 198

Source: Jensen and Malter (1995) for 1987-89; Castilla (2012) for 2010.
Note: ha = hectares.
[a] Excludes 30,000 ha of glass houses, which were mostly in Northern Europe.

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[2] Low tunnels are tunnels normally up to 1 m in height, and do not allow workers to walk inside them. In contrast, high tunnels are structures in which all crop-related work is done inside. High tunnels are a simplified variant of greenhouses (Castilla 2012).

[3] Liu, He, and Yan (2014) suggests that in China, the area reached about 20 million ha by 2011, which is significantly higher than the estimate of 9.87 million ha for the whole Asia by Castilla (2012).

Importantly, Asia and the Mediterranean region have accounted for much of the areas, as well as the growth during this period. Furthermore, despite these growths, the areas under protected agriculture is still small compared to total arable land. Even in Asia, areas under mulching and greenhouses are in the order of about 2 ~ 4 percent and 0.4 percent of the arable land of about 500 million ha. Therefore, protected agriculture has spread in very specific pockets around the world.

Within Asia, China and Japan have accounted for much of area under the protected agriculture. In China, the areas under plastic film mulch have grown from almost nil in the late 1970s to 20 million ha in 2010, which is approximately 20% of arable land (Table 2).[4] Similarly, the share of area under greenhouses has grown to about 2% by early 2010s, or about 6% of areas under vegetable and fruits (for which protected agriculture is predominantly used).[5] Using similar calculations, plastic film mulch and greenhouses have also spread to sizes of areas that are equivalent to 22% and 8% of vegetable and fruits areas, respectively, by 2012 (Table 3). These two countries can serve as cases where protected agriculture has spread to considerable scales, which some other Asian countries might be able to set as a target in the long-term.

Table 2. Growth of certain types of protected agriculture in China

	1981	1991	1999	2011
Plastic film mulch (million ha)	0.02	5		20
% of arable land	0	4		20
Greenhouses (million ha)	0.1	0.5	1.4	2.0
% of arable land	0.1	0.4	1	2
% equivalent to gross harvested areas for vegetable and fruits[a]	2	4	6	6

Source: Jensen and Malter (1995) and Liu, He, and Yan (2014) for plastic film mulch. Janke, Altamimi, and Khan (2017), Wang et al. (2017) for greenhouses.
Note: ha = hectares.

Table 3. Growth of certain types of protected agriculture in Japan

	1969	1975	1980	1990	1999	2012
Plastic film mulch (1000 ha)				155	143	133
% of arable land				3	3	3
% equivalent to harvested areas for veg and fruits[a]				19	21	22
Greenhouses (1000 ha)	11	22	32	45	54	46
% of arable land				1	1	1
% equivalent to harvested areas for veg and fruits[a]	1	2	3	5	8	8
Greenhouses with temperature control (1000 ha)						20

Source: Japan, MAFF (2018b).
Note: ha = hectares.

For commodity levels, the use of protected agriculture can be a near-dominant mode of production *for a particular set of crops* in the long-run. For example in Japan, the shares of greenhouse production to total production for tomato, cucumber, strawberries, have risen from 34%, 49% and 81% in 1975 to 86%, 62% and 86% in 2012, respectively (Table 4).

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[4] The cost of mulch has been reduced because the mulch used is a very thin film rather than the thicker film used in other countries (Jensen and Malter 1995).

[5] Importantly, the growths of protected agriculture in China have been partly led by the significant overall growth of areas under vegetables and fruits, which have tripled between 1990 and 2010.

Table 4. Japan – the share of greenhouse production to total production of selected crops

Crops	Share (%) of greenhouse production to total production in different years			Greenhouse area in 2012 (ha)	Share (%) of greenhouse area to total crop area in 2012
	1975	1983	2012		
Tomato	34	54	86	7336	61
Spinach			29	4232	20
Cucumber	49	57	62	3995	34
Strawberries	81	89	86	3863	68
Total				46449	

Source: Figures for 1975 and 1983 are from Jensen and Malter (1995); Figures for 2012 are from Japan, MAFF (2018b).
Note: ha = hectares.

Mediterranean region is the second-most widely adopted regions for protected agriculture in the world. There, greenhouses and low tunnels have expanded to the size of areas that are equivalent to 3% of vegetable and fruits areas in the region, and 8% of vegetable areas (Table 5).

Table 5. Protected agriculture in Mediterranean area (2006)

Countries	Greenhouses (ha)	Low tunnels (ha)	Ratio to vegetable + fruit areas (vegetable + fruit areas = 100)	Ratio to vegetable areas (vegetable areas = 100)
Spain	53,843	13055	3	18
Italy	42,800	30000	4	13
Turkey	30669	17055	2	5
France	11500	15000	2	11
Morocco	11310	3770	3	7
Egypt	9437	25000	3	5
Israel	6650	15000	18	33
Algeria	6000	200	1	2
Greece	5000	4500	3	7
Syria	4372	50	1	3
Lebanon	4000	700	5	18
Libya	3000		5	16
Portugal	2700	100	1	3
Jordan	1989	718	5	7
Tunisia	1579	7316	3	7
Albania	415		1	1
Cyprus	280	280	2	14
Malta	55	102	2	3
Total	200639	132846	3	8

Source: Castilla (2012 p.8).
Note: ha = hectares.

For the rest of Asia, the spread of protected agriculture has remained fairly low. For example, in India, as of 2009, only 0.56% (1,100ha) of 167,000 ha under flower cultivation was under protected agriculture (Sopan 2011), even though flowers are another commodities for which protected agriculture is used in more advanced countries. In Middle Eastern countries like Qatar, the share of greenhouse production has remained relatively low even for crops like tomatoes (Moustafa 2010). In Sri Lanka, protected crop cultivation had not been introduced until 1997 (Wijerathna, Weerakkody, and Kirindigoda 2014). In Oman, research in protected agriculture began in 1992 with the screening and evaluation of cucumber, tomato and sweet pepper in plastic houses (Moustafa et al. 1998).

2.2 Key patterns

The spread of protected agriculture has exhibited certain key patterns, which are likely to apply to other Asian countries in the future.

2.2.1 Variations within the country

The spread of protected agriculture has been uneven within each country. In China, out of 23 provinces, most protected agriculture has spread in Shandong, Henan, Jilin, Gansu provinces (Jiang 2009). In Kuwait, Wafra and Abdally accounted for about almost all protected agriculture (Moustafa et al. 1998). In Jamaica, 83% of greenhouse capacity located in just 5 of Jamaica's 14 parishes – Manchester, St. Ann, St. Elizabeth, St. Mary (Moulton 2015). In Turkey, greenhouses and tunnels in 2004 were mainly located in the Southern Mediterranean and in the Western Ege coastal region. Specifically, Adana, Icel and Antalya districts account for 85% of all protected agriculture area in the country (Anaç 2004). In Mexico, out of 31 states, 3 top states (Sinaloa, Jalisco and Baja California) account for close to half the share in 2011~2014 (de Anda and Shear 2017 Table 2). In India, anecdotal evidence suggests that a significant share of protected agriculture is found in Maharashtra, including Pune which is a major flower producing district (Gondkar, Singh, and Rao 2016).

In Japan, the adoptions are relatively more evenly spread, disproportionately higher shares are found in suburbs of Tokyo, as well as Kyushu Island (Japan, MAFF 2018a).

2.2.2 Scale of operations

Around the world, a majority of farms practicing protected agriculture are small-scale in terms of farm areas (although their production values are often large).

In Mexico, average sizes of units of protected agriculture are generally 0.5 ha for greenhouses, and in the similar order for other types (de Anda and Shear 2017, Table 1). In Mexico, enterprises of these scales earn about US$10 ~ 20 / m^2, or US$100,000 ~ 200,000 / ha of incomes (Vargas-Canales et al. 2018).

In Pune district, the Maharashtra state of India, typical flower-producing enterprises using protected agriculture earn net income of 500,000 – 1,000,000 rupees / year, employing 4 ~ 15 people (Gondkar, Singh, and Rao 2016). Similarly, 60 protected agriculture enterprises interviewed in Pune in 2011, were typically earning about US$7,000 – US$13,000 / year (mostly earning less than US$13,000 from protected agriculture, most of which employing less than 16 workers (Sopan 2011 p.45).

In Jamaica, individual farmers account for 81% of the Jamaica Greenhouse Growers Association (JGGA) members across the island. Among JGGA greenhouses, those with less than 15,000 square feet (about 0.14 ha) account for 90 percent of all greenhouses, and 50 percent of total capacity (Moulton 2015).

In Yemen in the late 90s, surveyed greenhouses had typical areas of 324 ~ 540 m^2, with common dimensions of 6 by 54 m, or 9 by 60 m, and height of 3~3.5 m (Moustafa et al. 1998). There, the life of plastic was also short, typically 1.5 ~ 2 years.

In Almeria region of Spain, widely known for the one of the world's most dense concentration of about 27,000 ha of greenhouses, greenhouses are operated mostly by small-to-medium-size farms (1.7ha) and run as family businesses (Acebedo, Tunez, and Bienvenido 2008). A majority of greenhouses are of medium-level technologies, using natural day radiation and winds to heat / cool greenhouses, rather than complex control systems.

2.2.3 Specificity of crops

The use of protected agriculture has often been associated with a relatively fewer number of crops. In the 2000s, among the major adopters of greenhouses and tunnels in the world, three crops, *tomatoes*, *cucumbers*, and *sweet peppers*, commonly appeared as the three most important crops (Lamont 2009, Table 1). These assessments have been also consistent with actual studies in various countries. For example, in Turkey, among approximately 40,000 ha of protected agriculture for vegetables in 2004, tomatoes and cucumbers accounted for 38 and 26 percent, respectively (Anaç 2004). In Jamaica, bell peppers and tomatoes are grown on 70 percent and 1/3 of greenhouses, while other specific vegetable crops are grown in at most 10 percent of greenhouses (Moulton 2015). In Kuwait, in the late 90s, tomatoes and cucumbers accounted for 90% (Moustafa et al. 1998). As was mentioned above, in Japan, tomato, cucumber, spinach and strawberries accounted for about 40 percent of all greenhouses (Table 4). In Qatar in 2006/07, cucumber, green beans, tomatoes, and sweet peppers accounted for 73, 7, 6.1, and 2.8 ha out of 92.2 ha of area under greenhouse in the country (Moustafa 2010).

Vegetables are also the most common crops grown with protected agriculture, while other commodities like flowers or ornamentals, fruits (except strawberries) are generally rare. In Turkey, out of 42000 ha in 2004, vegetables accounted for 95% (Anaç 2004).

In contrast, not all crops are suitable for indoor cultivation. These include grains and livestock. (de Anda and Shear 2017).

2.2.4 Markets

Typical markets for crops produced in the greenhouse vary by countries. They are mostly produced for domestic markets in the case of China or Japan. In contrast, in the 2000s, most greenhouse tomatoes produced in Mexico were sold in the US or Canada (Cook and Calvin 2005; USDA-AMS 2005; Cook 2007; Bernal et al. 2010). In Mexico, the largest exporter of greenhouse tomatoes was Desert Glory, a US firm operating in Jalisco and Colima, which shipped tomatoes year-round, taking advantage of the region's mild climate (Cook and Calvin 2005; Bernal et al. 2010). In the areas with hot, humid summers, like Sinaloa in Mexico, greenhouse tomatoes used to be produced only during the winter (Padilla-Bernal et al. 2015). However, some large exporters in these regions have also started experimenting with more modern greenhouses with more advanced control functions (Bernal et al. 2010). The growth of tomato exports from Mexico has been substantial, to the extent that the United States has actually seen a decrease in areas under protected agriculture recently (de Anda and Shear 2017).

2.3 Relevant technological aspects

The literature on protected agriculture is large. However, the literature on existing protected agriculture in developing countries is generally limited, and glancing through them offers some insights into the types of issues that may be relevant for countries like India that have yet to see the spread of protected agriculture.

Tunnel height. Tunnel heights have also been an important element. As described above, higher-tunnels make it easier to work on the soil or to conduct various crop management activities, as workers can walk in. Given the technological simplicity, low tunnels tend to be adopted first, and followed by the high tunnels. This was the case in China, where low tunnel greenhouses spread faster in the 1990s, while high tunnel green houses have spread faster since the late 1990s (Jiang 2009).

Covering materials. In addition to the material variations, often-reported variations in covering materials include thickness and the use of an ultraviolet-ray inhibitor (UVI) to increase its durability. For materials, plastic including polyethylene (PE) sheet is still common in most developing countries, although glass has been slowly taking off.

Oftentimes, covers are thicker for high-tunnels, and thinner for low tunnels. For example, in late-90s Bahrain, the thickness of covers ranged from 38 µm for low tunnels to 250 µm for walk-in tunnels (Moustafa et al. 1998). There, UVI, when used for cover materials, generally increased their durability by 2-3 additional years (Moustafa et al. 1998). In the whole of the Arabian Peninsula in the 1990s, the most common type of greenhouse was the single-span tunnel plastic-house covered with PE sheets of 200 µm thickness (Moustafa et al. 1998).

Ultraviolet (UV) stabilized plastic film, when used, affects temperature control efficiency. Worldwide, by 2011, nearly 90% of the new greenhouses were being constructed using UV-stabilized polythene sheets as the glazing material (Sopan 2011 p.44). In Maharashtra, India, in UV stabilized plastic film covered, pipe framed polyhouse, the day temperature is higher while the night temperature is lower than the outside (Sopan 2011).

In some structure, mesh shades made of synthetic fibers are used instead of plastic. Such examples are found in Mexico (de Anda and Shear 2017). In last-90s Bahrain, white-fly-proof clear fine mesh was often used to block white flies from entering the houses (Moustafa et al. 1998).

Variations among different types of glass are also reported. For example, in late-90s Kuwait, 15 percent of greenhouses had glasses, and their types of glass ranged from standard glass to fiberglass or acrylic materials (Moustafa et al. 1998). Similarly, in Qatar in 1995, the covering materials used were typically one of PE, fiberglass and glass (Moustafa 2010). The use of glass, fiberglass has been often associated with greater use of temperature control. For example, in Qatar in 2010, pad-and-fan cooling systems were used in the glass, fiberglass greenhouses while with the plastic tunnels only 4% were cooled (Moustafa 2010).

Shading structure. Shade-houses are structures that are related to greenhouses but differ in a sense that the former is intended to limit sunlight, while the latter often aims to allow more sunlight in, faster than heat can escape the structure. In Zacatecas state, Mexico, where protected agriculture grew from 37 ha to 184 ha between 2001 and 2007 (among which 95% are used for tomato production) shade-house type structures are used in about 10 percent of the area (Bernal et al. 2010). Shading was also commonly used by shade net cover in late-90s Bahrain (Moustafa et al. 1998).

Type of climate controlled. In late-90s Kuwait, 85% of greenhouses were of plastic rather than glasses. Among them, about 2/3 were uncooled green houses, while 1/3 were cooled greenhouses (Moustafa et al. 1998). Humidity is controlled by openings on the cover, and cooling pad. In Maharashtra, the low-cost manual greenhouses often have openings, which are kept open for 1-2 hours during the day, especially in the morning to reduce the level of humidity inside (Sopan 2011). At the same time, cooling pads are used for humidifying the air entering the house when needed (Sopan 2011). In late-90s Bahrain, about 10% of greenhouse areas were using ventilation, by opening the tunnel side, to remove humidity inside the house and prevent fungal and bacterial diseases (Moustafa et al. 1998). Ventilation facilities are also attached to the roof. In 2006, galvanized and PE-covered greenhouses (9x30 m) having side and roof ventilation facilities were installed for vegetable production in three districts of Balochistan in Pakistan, which became popular among growers due to the simplicity and ease of construction (Khan et al. 2011).

Climate control materials may have a shorter life than the entire structure. For example, in Maharashtra, while the polyhouse frame has a life span of about 20 years, glazing materials[6] usually have a life of only two years (Sopan 2011).

Other modes of temperature control have been increasingly studied in the literature, including that in developing countries. A split-roof system, which helps extract the hot air at the top of the structure, is being studied for improved temperature control (DeGannes et al. 2014; Sahadeo, Ekwue, and Birch 2017). Wind machines have been studied, which could prevent frost by moving air over the endangered plants (Jensen and Malter 1995 p.10). For example, wind machines in the 100 hp class are expected to provide protection of 2C or more for an area of 3 – 3.5 ha on a clear, calm night (Jensen and Malter 1995 p.10).

Frame. Frames also varied in developing countries, from bamboos to galvanized iron (GI) pipe of varying thickness. In Maharashtra, India, low-cost (entirely manual) greenhouses generally used bamboos with rope and nails to support polythene sheet of 700 gauge, while medium-cost greenhouses often consist of the arc-shaped house framed with GI pipe of 15 mm bore (Sopan 2011). In Bahrain, in the late-90s, typical frames used for greenhouses were made of galvanized steel pipes of 22 mm in diameter, aluminum or coated steel pipes (Moustafa et al. 1998). Similarly, in Jamaica, by 2015, metal had become the most common type of frames used, surpassing wood (Moulton 2015).

Size of structure. Typical structures of high-tunnels erected as single-spans in Bahrain in the 1990s were about 4-5 m wide, 25-30 m high and 36--40 m long (total surface area 140-180 m^2) (Moustafa et al. 1998).

Energy structure. The use of renewable energy for protected agriculture is still limited. However, research has progressed in China in recent years on Photovoltaic (PV) greenhouses. In various locations in China, thanks to the declining costs of PV-related technologies, PV-greenhouses are becoming increasingly affordable, typically requiring a payback period of fewer than 9 years (Wang et al. 2017).

Other technologies. Other technologies used in Mexico in combination with greenhouses include irrigation, which can be programmed, as well as computerized and precision injections of CO_2 using sensors and devices, or thermal screens for the control of the illumination and cultivation of plants (de Anda and Shear 2017). Drip irrigation was also commonly used. For example, by 1995 in Qatar, drip irrigation had been used in all greenhouses except for a few where sprinkler or flood systems were used (Moustafa 2010).

While soil is commonly used as the base for production, non-soil methods like hydroponics are also used (albeit generally rare) as in parts of Mexico (de Anda and Shear 2017). The use of hydroponics is still generally limited. For example, in Oman, only 1% of protected agriculture uses a hydroponic system (ICARDA 2011). Similarly, in Qatar, direct planting in soil still accounted for 86% in protected agriculture, while production in sand bags[7] or water culture / hydroponics accounted for only 14% and 0.2% (Moustafa 2010). Soil culture, instead of non-soil culture, also still dominates greenhouse production in Jamaica (Moulton 2015).

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[6] Glazing materials are used to control thermal performance of windows set up on the greenhouse structure.

[7] Sand bags, which can be easily replaced after crops, have the advantages of preventing soil infection by nematodes and pathogenic organisms which can cause root and plant damage if not sanitized regularly (St. Martin and Brathwaite 2012).

Mulching is also sometimes combined with greenhouses. In late-90s Bahrain, ground-mulching with black PE film inside the greenhouses, was fairly common practice, and intended to reduce water evaporation, raise soil temperature, eliminate weeds, prevent salt accumulation around the plants, and lead plants to early production (Moustafa et al. 1998).

Improved varieties also have potentials to complement protected agriculture. For example, "large yield increases (20% in tobacco) have been associated with genetically modified plants, which has been designed to use light more efficiently, through the change of bandwidth of LED [light-emitting diode] lighting" (Devlin 2016 cited in Pinstrup-Andersen 2018).

2.4 Economics – intermediate, modern altogether (cost, resource requirements)

This section discusses a few key issues regarding the economics of protected agriculture. The section does not go into a comprehensive review of the literature, but rather highlights key economic factors (productivity, costs, key inputs use requirements), with a particular focus on the protected agriculture that is already practiced in developing countries.

2.4.1 Productivity

Where protected agriculture is actually practiced, on-farm (not experimental) productivity, like outputs per land or water used, is typically several times higher than conventional farming, although obviously production costs are also higher. Protected agriculture therefore has the potential to significantly raise land and water productivity, where doing so is a priority (Table 6).

Table 6. Productivity of protected agriculture in selected developing countries

Country	Year	Productivity of	Tomato		Cucumber		Pepper	
			Open field	Green house	Open field	Green house	Open field	Green house
Kuwait	1995	Land		50		125		50
Mexico	2017	Land	40 ~ 60	120 ~ 600				
Qatar	2006/07	Land	30	139	15	100	6	51
		Water	3	19				
UAE	2006/07	Land	40	170				
		Water	6	28			1	4 ~ 8

Source: Kuwait = Moustafa et al. (1998); Qatar, UAE = Moustafa (2010); Mexico = de Anda and Shear (2017).
Note: ha = hectares; UAE = United Arab Emirates. Land productivity is ton / ha; Water productivity is in kg/m^3.

Productivity by different types of protected agriculture. Productivity also varies by the level of technologies employed in protected agriculture. For example, in 2006, average greenhouse tomato yield in Mexico was about 130 tons / ha, much lower than the US and Canada yields of more than 450 tons / ha (Cook 2007; Bernal et al. 2010). Bernal et al. (2010) attributes this to the type of greenhouses used in Mexico, which were mostly shade houses and macrotunnels to permanent greenhouse structures with limited or passive environmental control.

Similarly, the productivity of land or water is found to vary considerably between different levels of sophistication of protected agriculture used, ranging from low tunnels vs. green houses, temperature control (cooled or uncooled), and types of covering materials used (fiberglass or others) (Table 7).

Table 7. Productivity of different types of protected agriculture in selected developing countries

Country	Crop	Productivity of	Low technology	Medium technology	High technology
Mexico	Tomato	Land	120 ~ 150	200 ~ 250	600
			Uncooled plastic tunnels	Cooled plastic tunnels	Fiberglass greenhouse
Kuwait	Tomato	Land	100	120 ~ 150	160
	Cucumber	Land	40	60	80
				None-cooled green house	Cooled green house
Qatar	Sweet pepper	Land		30 ~ 60	80
	Sweet pepper	Water		4 ~ 6	8

Source: Kuwait = Moustafa et al. (1998); Mexico = de Anda and Shear 2017; Qatar = Moustafa (2010).
Note: ha = hectares. Land productivity is ton / ha; Water productivity is in kg/m^3

2.4.2 Costs

Fixed costs. The costs of protected agriculture facilities used in developing countries vary depending on the level of sophistication as well as sources (Table 8).

Table 8. Cost of protected agriculture facilities

Region / country	Wooden greenhouse	Metal greenhouse	Other costs
Arabian Peninsula countries	US$13 / m^2 (1990s)		
Jamaica	US$10-14 / m^2 – for 50 m^2 Untreated wood - US$84253 / ha Treated wood - US$131998 / ha - US$245756 / ha	Imported from Spain – US$63 / m^2 in 2009 (total of 960 m^2) Imported from US – US$65 / m^2 in 2009 (total of 768 m^2) Imported from Israel – US$40 / m^2 in 2009 Imported from China – US$27 / m^2 in 2009 – design, construction were done in Jamaica	
Mexico	US$5/m^2: light metal structures, plastic, mesh shades made of synthetic fiber	US$19 / m^2: semiautomatic processes US$115 / m^2: fully automated	
Myanmar	Bamboo greenhouse – US$7 ~ 10 / m^2	Traditional greenhouse for tropics – US$50 / m^2 (Kotzen 2010 p.70)	
Pakistan (Balochistan)		10.3 / m^2	
Sri Lanka		27 / m^2	
Trinidad and Tobago			Replacing and cleaning plastic: US$2,400 to US$2,700 for a 930 m^2 system

Source: Arabian Peninsula countries = Moustafa et al. (1998); Jamaica = Jiang (2009) and Moulton (2015). Mexico = de Anda and Shear (2017); Myanmar = Kotzen (2010); Pakistan = Khan et al. (2011); Sri Lanka = Kumara, Weerakkody, and Epasinghe (2015); Trinidad and Tobago = Sahadeo, Ekwue, and Birch (2017).
Note: ha = hectares. Where information is in local currency, figures are converted into US$ using historical exchange rates.

While the information of the breakdown of costs is generally limited in developing countries, an example is seen for the low-cost technology in Pakistan (Table 9). Galvanized frame accounts for about half the total costs, while plastic covering and insect proof net account for 25 percent. According to the Khan et al. (2011), given the assumed life of each component, the annual costs may be about 1/15 (0.7 / m^2 instead of 10.3 / m^2) of the investment costs.

Table 9. Initial investment for protected agriculture tunnel construction in Pakistan, Balochistan (Khan et al. 2011)

Item	Initial cost (US$)	%	Use full life year	Annual cost (US$)	%
Galvanized frame	1471.4	53	20	73.7	39
Plastic Covering	367.8	13	10	18.4	10
Insect proof net	313.4	11	20	15.7	8
Black plastic mulch	46.3	2	2	23.2	12
Sockets, valves, pipes, elbow etc.	118.2	4	10	11.8	6
T-Tapes and PVC pipes	108.1	4	10	10.8	6
Water tank	133.3	5	10	13.3	7
Water pump	100.0	4	15	6.7	4
Site preparation	50.0	2	10	5.0	3
Assembly	83.3	3	10	8.3	4
Total	2792.0	100		186.8	100
Per m^2	10.3 (103,000 / ha)			0.7 (7,000 / ha)	

Source: Khan et al. (2011).
Note: ha = hectares.

Table 10 summarizes variable costs in various types of greenhouses, crops and countries that report figures. Generally, variable costs vary from 0.6 US$ / m^2 in traditional metal greenhouses, to US$3 ~ 8 / m^2 in more modern metal greenhouses. Among the costs, water and energy often account for non-negligible shares.

Table 10. Variable costs in protected agriculture (US$ / m^2)

Region / country	Crops	Traditional metal greenhouse	Modern metal greenhouses (US$ / m2)
Kuwait	Strawberries		8 - Cooled GH Vertical, Hydroponics (Water = 8%, Energy = 1%) 3 - Cooled GH Soil (Water =24%, Energy = 2%)
	Musk melon		1.6 - None- cooled GH Hydroponics (Water =5%, Energy = 41%)
Pakistan (Balochistan)	Cucumber	0.6 (6,000 / ha) (Irrigation labor = 22%, Energy = 13%)	
UAE	Strawberries		3 - Open field Hydroponics (Water = 9%, Energy = 1%)

Source: Various including Kuwait, UAE = Moustafa (2010), Pakistan = Khan et al. (2011).
Numbers in parentheses indicate the cost share of water and energy.
Note: GH = greenhouses; ha = hectares; UAE = United Arab Emirates.

Water and energy use. Water and energy account for some of the most important inputs in protected agriculture, and this is especially so as the technologies become more sophisticated. In Jamaica, a daily supply of water of 1 ~ 2 liters per plant is recommended (Moulton 2015). In

Qatar, water use of about 3,000 liters / m^2 is common practice, although the figures vary from about 700 liters / m^2 for strawberries to about 3,000 liters / m^2 for tomato, cucumber, sweet peppers, and close to 5,000 liter / m^2 for lettuce (Moustafa 2010).

In Jamaica, water is sometimes purchased from private truckers, at the cost of approximately US$120 for about 15,000 liters (Moulton 2015).

In a literature survey of greenhouses in different countries by Hassanien, Li, and Lin (2016), the annual electrical energy consumption per unit greenhouse area is among 0.1–528 kWh per m^2 per year (Wang et al. 2017).

2.4.3 Other challenges

Knowledge. The learning curve in greenhouse management takes 3 to 5 years (Bernal et al. 2010). The knowledge is often reported lacking among potential adopters, on various aspects of protected agriculture. In Pune district in Maharashtra, where a significant share of protected agriculture in India is concentrated, insufficient knowledge on cool chain management, scientific knowledge on protected cultivation technology, harvesting knowledge, are among the major constraints reported (Sopan 2011). Similarly, in China, the lack of essential knowledge is reported as one of the major constraints (Jiang 2009).

Pests and diseases. Pests, such as arthropods and nematodes, and diseases are the main problems that face many medium and low-tech greenhouse in Mexico (de Anda and Shear 2017). In Pune, India, new pests and diseases are also found to emerge following the introduction of more control of temperature and other production environments (Sopan 2011). Where there is a high concentration of greenhouses, pests were often found to expand easily across units by proximity (Almeria in Spain – Acebedo, Tunez, and Bienvenido 2008).

At the same time, excess control of insects could have negative effects. For example, “Pollination is something that needs serious consideration because insects are crucial in the process of the production of seeds and fruits. Therefore, given that the technology is an insect-free environment, pollination has to be done by hand, which is labor intensive and could affect production costs and diminish profits.” (de Anda and Shear 2017).

Heat inside the facility. Sometimes, heat can accumulate excessively inside the facilities, such as reported in China (Jiang 2009). A number of measures have been proposed as solutions. For example, an insect net with a low number of meshes (large hole) can be used. High mesh insect net is effective to prevent insects from entering and attacking crops in greenhouses, but will block the air cross movement and build-up the heat inside the greenhouse; insect net with less than 20 meshes is strongly recommended to cover the walls of greenhouses (Jiang 2009).

CO2 in closed environment. CO_2 tends to accumulate inside the facilities. Generally, higher CO_2 inside the facilities is believed to have positive effects on production (Nguyen 2017 – cited in Pinstrup-Andersen 2018), but the excessive level can hurt human (Perez 2014). Furthermore, “recent research shows that while increased CO2 promotes plant growth, it alters plants’ nutritional composition, increasing carbohydrates (starches and sugars) and decreasing concentrations of protein and minerals such as iron and zinc (Loladze, 2014).” (Taylor 2018). Similarly, humidity can also accumulate in a closed environment (Perez 2014).

Other effects. The controlled environment is also expected to have various effects. For example, for strawberry production, even in controlled environments, flavor characteristics change over time in ways not yet fully understood (Perez 2014 p.57). It is recommended that, selecting day-neutral strawberry cultivars can help enable long-term, affordable production in an off-Earth, plant-based life support setting under a variety of photoperiod environments.

Wastes from protection materials. One of the commonly reported side-effects of protected agriculture is the production of waste materials, such as mulch or other plastics, among others. In Japan, as the use of plastic mulch grew, disposal of waste mulch had become an important process of environmental management (Jensen and Malter 1995). In 1985, the total amount of waste had reached 165,892 tons, including waste materials from greenhouses and row covers, as well as plastic mulches. Similarly, in Mexico, protected agriculture is found to produce large amounts of solid residues, including plastics from renovating the structure covering, irrigation tubes and containers, among others, and any substrates if used in place of soil (Padilla-Bernal et al. 2015).

Measures had been put in place to deal with these wastes. Since 1970, Japan has treated plastic waste (such as mulch) under the law of industrial wastes, primarily through three methods (recycling, burial, incineration) (Jensen and Malter 1995). In Finland, recycling of plastics has been a major business for a private company producing heavy-duty plastic sacks (Jensen and Malter 1995).

3 Precision agriculture

The second example of a frontier production system is precision agriculture. Precision agriculture refers to a suite of technologies that may reduce input costs by providing the farm operator with detailed spatial information that can be used to optimize field management practices (National Research Council 1997; Schimmelpfennig 2016). This section first briefly describes the adoption trends around the world, and then summarizes the key set of aspects that have been gaining attentions and commonly studied in the literature focusing on developing countries in Asia.

3.1 Adoption trends around the world

The adoptions of precision-agriculture technologies have, so far, mostly been limited to parts of developed countries. In Australia, by 2013, 90 percent of farmers had been using some type of precision agriculture, and 20 percent of farmers had been using yield mapping and variable rate fertilizer application (Bramley and Trengove 2013). In Germany, about 10 ~ 30 percent of farmers were using some form of precision agriculture in 2016 (Paustian and Theuvsen 2017 - cited in Taylor 2018). Keskin & Sekerli (2016) provides related statistics in some other developed countries.

In the United States, the use of precision agriculture started growing in the 2000s, and spread considerably, although at varying rates across crops and the types of precision agriculture (Schimmelpfennig 2016). In 2010 in the United States, yield monitoring has spread to almost 70 percent of maize and soybean areas, while the adoptions of variable-rate technology have also reached about 30 percent of the areas (Table 11).

Table 11. Adoption rates of various precision agriculture in United States (2010)

Crops	Technologies	% of farms adopting	% of areas
Maize	Yield monitor	48	70
	Yield map	25	44
	Soil GIS map	19	31
	Guidance system	29	54
	Variable-rate technology	19	28
Soybeans	Yield monitor	51	69
	Yield map	21	40
	Soil GIS map	16	28
	Guidance system	34	53
	Variable-rate technology	26	34

Source: Schimmelpfennig (2016).
Note: GIS = geographic information system.

In the United States, the progress on precision agriculture has varied across crops. Yield monitoring for cotton lagged behind grain yield monitoring (Watcharaanantapong et al. 2014). This is partly because of equipment problems associated with accuracy, calibration and maintenance of optical sensors; for example, compared to those for maize, development of reliable and accurate cotton yield monitors did not occur until 2000 when yield monitors had already been used on about one-third of corn and soybean area in the Corn Belt, respectively (Schimmelpfennig and Ebel 2011; Watcharaanantapong et al. 2014). Furthermore, even in the US, adoption rates are positively correlated with farm size. For example, the largest corn farms in the country, those over 2,900 acres, are twice as likely to adopt precision agriculture techniques as the average farm (Schimmelpfennig 2016; Taylor 2018). Precision-agriculture technologies for corns, which have spread substantially in the United States recently, are still not adopted by 88% of farmers cultivating less than 600 acres (Schimmelpfennig 2016).

In developing countries, the use of precision agriculture has been limited. In Malaysia, site-specific fertilization is being applied to rubber plantations, and other precision technologies have started being applied for oil palm, although not to rice fields (Mondal and Basu 2009). In Turkey, recently, international companies like Topcon sold about 60 auto-steering system in the Southern part of the countries along Mediterranean regions (Keskin and Sekerli 2016). The service providers of auto-steering service set up own reference station networks for positioning correction, and some farmers owning automatic steering use them to serve other farmers mainly in ridge tillage in cotton and corn cultivation (Keskin and Sekerli 2016). Similar service dealership related to precision agriculture is observed in Brazil as well (Borghi et al. 2016). Similarly in Turkey, an international company (New Holland) is planning to install yield monitors on about 500 combine harvesters countrywide in the last few years (Keskin and Sekerli 2016).

In India, technologies related to precision agriculture that have been adopted include drip and sprinkler irrigation, which have been growing steadily, although still accounting for only a fraction of irrigated areas in India (Kalubhai 2015). Similarly, while similarly accounting for a tiny fraction of areas within India, adoptions of laser-land-leveling technologies have been growing in parts of India, including Western Uttar Pradesh and Haryana (Tiwari and Jaga 2012).

3.2 Key aspects of precision agriculture assessed in the recent literature in developing Asia

The literature on precision agriculture is enormous and growing, including those in developing countries in Asia. Therefore we do not go into the details of each study. However, here, we highlight key aspects of precision agriculture that appear to be recognized as having potentials in applications in developing Asia, including South Asia, with references to relevant studies.

Overall issues. An increasing number of studies provide overviews of relevant aspects of precision agriculture in developing countries in Asia, showing the growing readiness and interests in various precision agriculture technologies in these countries, including Bangladesh (Das and Gope 2014), China (Sun and Li 2015), Pakistan (Mahmood et al. 2013), and India and other countries (Mondal and Basu 2009; Mondal et al. 2011; Mandal and Maity 2013; Dixit et al. 2014; Sharma et al. 2016; Kushwaha Raghuveer 2017).

For India, studies also provide overview of relevant issues for particular crops, or specific issues, including GIS based decision support system for precision farming of cassava (Soman, Byju, and Bharathan 2013), sugarcane (Patil, Nadagouda, and Al-Gaadi 2013), organic horticulture production (Yadav and Yadav 2014), the role of FDI on precision agriculture (Ahmed 2014), or the reviews of Wireless sensor networks for agriculture (Ojha, Misra, and Raghuwanshi 2015).

Research on the variability. Several recent studies have focused on showing how the production environments and yields vary within the small areas or plots. For example, yield variability for wheat is observed through the monitoring process in India (Chandel et al. 2014) and Pakistan (Farid et al. 2013). Soil quality, such as acidity and nutrients, among others, are also found to vary considerably within the selected plots in Karnataka (Shivanna and Nagendrappa 2014). Studies in China also show the soil spatial and temporal variability at the watershed scale in upper reaches of the Yangtze River in southwestern China (Yang, Zhu, and Li 2013). Similar spatial heterogeneity of soil is found in Southern Iran (Emadi, Baghernejad, and Maftoun 2008). In India, Vinod (2017) classifies the topographic position index and landforms of Kerala State using Jenness algorithm, for the purpose of applying precision agriculture (Vinod 2017).

Such consistently high within-plot, and local-area variability generally indicate the potential gains from applying precision agriculture in Asia despite the dominance of smallholders in the region. At the same time, these studies suggest that, continuous and expanded research to better understand the nature of within-plot variability in yields and soils is important in India, as well as many other parts of Asia.

Big data for agriculture, internet of things, general systems. Recent research in the field of precision agriculture in developing Asia has also focused on the development of efficient and suitable systems to enable the use of big data for agriculture, and the application of the internet of things (IoT).

Singh (2017) discusses the strategies for developing data warehouse / big data technologies in India. Singh (2017) shows that current major sources of data in India include (i) Kisan SMS portal system, (ii) Community Information Center, (iii) AGMARKNET (http://agmarknet.dac.gov.in), (iv) e-choupal, and (v) agriwatch.com, which can be further integrated and augmented. Channe, Kothari, and Kadam (2015) and Singh (2017) proposed doing so using five key technologies, IoT, sensors, cloud computing, mobile computing, and Big-Data Analysis.

In China, Yamin et al. (2016) examines improved farming information collection system which they propose, which achieves the detection and collection of the chlorophyll relative content, temperature, humidity, light intensity and geographic location (using Cloud).

In Indonesia, using the case of mushroom production, Mahmud et al. (2018) investigates a proposed system that connects temperature humidity sensor and others to Wifi module, which becomes IoT sensors that send a big amount of data to the internet for monitoring and assessment. They find that the system seems effective, automatically on and off the irrigation system to put the temperature at an optimal level.

The strong interests in these issues suggest that, there is significant scope for improving the performance of precision agriculture through modifications big data, IoT systems, and information collection systems. Continuous research on related issues is likely to remain important.

Improvement of remote-sensing image analyses, optical sensing. Recent research in the field of precision agriculture in developing Asia has also extensively focused on the efficiency of various types of image analyses and optical sensing.

Studies investigated various types of technologies for image processing or mapping. Yue et al. (2016) studies new detection methods with color and depth images based on Kinect sensor technology in China. Jayashree et al. (2015) used fuzzy cognitive map (FCM) for assessing coconut production level in Kerala's Malabar region, while Srivastava et al. (2015) uses hyperspectral model to monitor soil organic carbon in Indo-Gangetic Plains of Punjab, India.

A substantial number of studies investigate the effectiveness of collecting various information associated with agricultural production. These include species identifications by infrared spectrum characteristics (Yu et al. 2014b), assessment of soil moisture levels (Tingwu and Yuequn 2013) through a near infrared reflection (NIR) soil water sensor, detection of soil nutrient contents (Dong et al. 2014; Lu et al. 2013 which uses laser-induced breakdown spectroscopy; Sankpal and Warhade (2015) providing the review of sensing technology and other portable methods used to determine the soil nutrients NPK in India.), soil quality / pollution measurements in China (Wang et al. 2013).

The research has also focused on the evaluations of canopy Nitrogen contents of various crops (Yu et al. 2014a). Nitrogen is one of the critical determinants of crop yield and grain quality, as well as canopy photosynthetic capacity and carbon-nitrogen cycling in the earth ecosystem (Yu et al. 2014a). Accurately capturing the nitrogen contents in the canopy is believed to be one of the important tasks which precision agriculture is expected to achieve. However, estimation is complicated due to seasonal dynamics of plant morphophysiological variation, and there is a significant scope for research to improve this effectiveness (Yu et al. 2014a). Related studies examine various technologies for this purpose of estimating nitrogen contents in the plants, including de-noising of near infrared image (cucumber in greenhouses in China, Yang et al. 2013b), ground-based optical sensing over the crop canopy for rice in Korea (Kim and Hong 2008) which relies on the fact that crop nitrogen content is closely related to the greenness of plant leaves, active canopy sensors for assessing Nitrogen status for winter wheat (Cao et al. 2012).

Similarly, studies examine the potential of using spectral reflectance of objects. Othman, Steele, and Hilaire (2018) examines the use of surface reflectance climate data to study foliar chlorophyll content in pecan orchards within India. Yu et al. (2014b) examines the use of spectral reflectance to estimate the key agricultural parameter of orange leaves in China.

Other examples include the detection of dust concentration in henhouse – to mitigate harms to hens and workers' body in China (Li and Hu 2014), and prediction of reference evapotranspiration with missing data using Artificial Neural Networks (ANNs) in Thailand (Pasupa and Thamwiwatthana 2013), and or detection of weeds through machine-learning (Behmann et al. 2015). Studies have also investigated the potential for tractor mounted Nitrogen-sensor, a remote sensing system which processes the real-time measurements using an onboard computer to produce sensor biomass data (Sharma et al. 2012), and measurements of weight of grains in grain tank in real time in China (Cong and Zhou 2013).

The strong interests in these issues suggest that, there is a significant scope for improving the performance of precision agriculture to gather various types of information about soil, plant biomass, nitrogen contents in crops, dust, evapotranspiration, weeds, among others. Continuous research on related issues is likely to remain important.

Efficiency of sensor. Recent research in the field of precision agriculture in developing Asia has also extensively focused on the efficiency of sensors and related technologies. Kumar and Chinara (2015) examines the energy-efficiency of a wireless sensor network, through a new proposed protocol that aims to enhance the network lifetime by reducing the per-node energy consumption and maintain the balance between energy consumption and energy disparity. Qiu et al. (2014) examines the design of intelligent greenhouse environment monitoring system based on ZigBee and embedded technology (Qiu et al. 2014), while Ye et al. (2013) studies improved information transmission, such as video wireless transmission system in China to address the information lag and poor timeliness of agricultural machinery operation (Ye et al. 2013).

Research also compares different types of sensors. In China, Crop Circle sensor-based precision N management is compared and recommended over GreenSeeker sensor method (Cao et al. 2015). Taihao and He (2014) examines the optimal locations of Wireless Sensor Network (WSN) nodes, taking into account the potential radio frequency signal loss due to particular planting density, using the case of corn in China (Taihao and He 2014).

The strong interests in these issues suggest that, there is a significant scope for improving the performance of sensors, including energy-efficiency, node placements, visual-functions, among others. Continuous research on these issues is likely to remain important.

Equipment design. Recent research in the field of precision agriculture in developing Asia has also studied the designs of various equipment used in precision agriculture. Some of the examples include locally-suitable indigenous yield monitoring device for grain combine harvester in India (Sharma et al. 2012), improved pesticides application through the proportional electromagnetic valve in China (Zhai et al. 2015), and variable rate fertilizer applicator with modified external grooved wheel fertilizer apparatus in China (Shiqiang et al. 2016). The development of equipment is also combined with research on complementary technologies. For example, Bharathi and Balachander (2017) examines the development of biofertigation materials like liquid microbial consortium, which do not clog the equipment, in Southern India.

Precision-application of inputs (seeds, chemicals, etc.) including variable rate technology. Recent research in the field of precision agriculture in developing Asia has also studied the roles of precision agriculture on optimal inputs and service uses, and their spatial allocations. These studies include spatial allocation of animal manure using GIS in China (Yan, Pan, and Yan 2018), precise pesticide application in India through the use of precision-tools like air-assisted sprayer (Tiwari and Jaga 2012), a constant flow valve in lever-operated knapsack sprayers that can help control pressure and flow (Eng, Omar, and McAuliffe 1999), precision seeds for direct vegetable sowing through pneumatic precision planter (for vegetable crops) or pneumatic seed-metering machine (for direct sowing of small vegetable seeds) (Ma et al. 1990; Tiwari and Jaga 2012). Research also examines the optimal N application and topdressing rates, using an active sensor in China (Xue et al. 2014), or simple, portable diagnostic tools (including chlorophyll meter (SPAD) and leaf color chart (LCC)) that can be used for in situ measurement of the crop N status in rice fields to determine the timing of N top dressing (Mondal and Basu 2009).

Research has also examined precision pest control (Karl & Willig 2007), for example, control of plant-parasitic nematodes (Stirling 2014), irrigation water management including real-time irrigation control (Prathyusha, Bala, and Ravi 2013), or laser-assisted precision land leveling piloted in India (Tiwari and Jaga 2012 p.141).

Unmanned aerial vehicle, robots, auto-steering. machine vision. Recent research in the field of precision agriculture in developing Asia has also increasingly examined the potentials of unmanned aerial vehicles (UAVs) for precision agriculture. Beard and McLain (2012) and Zhang and Kovacs (2012) review the overall potentials and issues associated with unmanned aircraft partly for the application in precision agriculture. Recent studies in developing Asia examine the potentials for using UAVs for monitoring wheat drought (Su et al. 2018), plant protection (Yang, Yang, and Mo 2018), or aerial spraying (Yin et al. 2018) in China, and its use for remote sensing, parcel area measurement, tree plants counting, or 3-dimensional plant mass calculation, in Indonesia (Rokhmana 2015).

Earlier studies in China also examined the potentials for using robots for various activities, including grafting, transplanting, spraying, mowing, harvesting, or grading and detecting (Libin et al. 2008). Worldwide, about 20,000 industrial robots in use in 2013, valued at $2.4 billion (United Nations Economic Commission for Europe (UNECE) cited in Yaghoubi et al. 2013). Out of this, 885 were used for field operation (including agriculture and forestry, as well as mining) (Yaghoubi et al. 2013).

Studies also examine the potential of autosteering for the application in precision agriculture. Bhagat et al. (2013) assesses the potentials for applying auto-steering for leveling, disking, row listing, and bed shaping / mulching, planting, spraying of chemical pesticides and liquid fertilizer, side-dressing, as well as the use of chisel plow and border disc, among others, in India. In China, Zhou et al. (2012) examines the potential for developing automatic navigation control for agricultural machinery, through mechanical guidance, machine vision guidance, radio navigation, and ultrasonic guidance.

The uses of machine vision technologies are also examined in detail by various studies. Zhao, Zhao, and Gao (2015) examines the use for the selection of seed, nondestructive tests of agricultural products, agricultural machinery navigation and crop growth information detection in China. Du, Ping, and He (2013) examines the application in surface defect detection and classification system for cherry tomatoes in China.

All these growing studies suggest the potentials for UAVs, robots, and the use of auto-steering and machine visions for precision agriculture, which have been recognized by the researchers.

Nano-technologies. Another area of growing interests in the literature on precision agriculture (including those in developing Asia), includes nano-technologies, for applications in crop nutrition balance, weed control, seed emergence, identity preservation and tracking (through nano-devices), real-time monitoring through nano-sensors (Subramanian and Tarafdar 2011), among others. Nano-fertilizers and their variants are being studied in Subramanian and Tarafdar (2011). In India, Bansiwal et al. (2006) develops a surface modified zeolite as a carrier of slow release phosphatic Fertilizer (Subramanian and Tarafdar 2011). Chinnamuthu (2010), reviewed in Subramanian and Tarafdar (2011), examines encapsulation of herbicides to regulate the release of herbicide molecules, including technologies studied in Tamil Nadu Agricultural University. Pandey (2018) summarizes the challenges for adopting agri-nanotechnologies (nano-based agro-chemicals, ceramic devices, filters; lamination methods) in India, including availability, synthesis, level of toxicity, health hazards, transportation challenges and incongruity of the regulatory structure.

Economics of precision agriculture in developing Asia. Because of the limited application so far of precision agriculture in developing Asia region, the information on the economics of precision agriculture in the region is limited. Knowledge has been, however, slowly accumulating.[8]

Shruthi, Hiremath, and Joshi (2018) examines the differences in incomes among pigeonpea growers in India using precision agriculture and non-users, and finds lower chemical fertilizer use and higher incomes per hectares of about 10,536.34 / ha. Similarly, Shruthi et al. (2018) finds similar differences among paddy growers in Karnataka. In Kerala, Franco, Singh, and Praveen (2018) finds that farm size and education level are some of the key socio-economic determinants of the adoption of precision agriculture for banana cultivation. Tey et al. (2018) examines the role of the informal social network, in addition to extension, on the spillover of information about precision agriculture in Malaysia. +

The cost of sensors varied between 200 ~ 600 per sensor in Iran in 2003 (Stombaugh, Dillon, and Shearer 2003), the costs have recently declined to around $100 per sensor (Taylor 2018 p.16), although the costs of software and hardware (a laptop, at least) need to be added.

The cost of a UAV equipped with a global positioning system (GPS) can range up to US$100,000 (Rango et al. 2009) and for that of a unmanned aircraft system (UAS) multi-spectral camera upwards of US$15,000 (Zhang and Kovacs 2012 p.700).

Profitability with and without precision-agriculture in various locations within India is examined in a few studies (Maheswari, Ashok, and Prahadeeswaran 2008; Shitu, Maraddi, and Sserunjogi 2015; Ramamoorthy and Gopu 2016; Kadam et al. 2017), among others. These studies generally suggest that the major contributions to the profitability of precision agriculture is reduced costs of plant protection inputs, and higher output revenues. However, much more research is needed to assess how the implications of different types of precision agriculture, and different characteristics of farms, given that, as mentioned above, precision agriculture technologies can be quite heterogeneous in many dimensions.

4 Vertical farming

Vertical farming is often referred to as a system of crop production which maximizes the uses of land by having a vertical design whereby plants, animals, fungi and other life forms are cultivated for food, fuel, fiber by artificially stacking them vertically above each other (Kalantari et al. 2017). The growing practices of vertical farming take advantage of many breakthroughs in building devices, materials, renewable energy systems achieved during recent decades (Heath, Zhu, and Shao 2012).

4.1 Trends in the world – vertical farming

The adoption of vertical farming around the world is still limited to a small number of pockets. However, the number has been growing gradually. A number of low-rise vertical farming projects have been built across cities around the world, and high-rise projects are being proposed (Al-Kodmany 2018). These start-up vertical farms are often subsidized by the government (Pinstrup-Andersen 2018). An estimate by Statista (2019) suggests that, the market values of vertical farming reached US$0.403 billion in 2013 and US$1.5 billion in 2016, out of

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[8] In the United States, where the use of precision agriculture is more widespread, GPS mapping technologies are estimated to generate a net return of 2%, guidance systems contribute a 1.5% increase, and variable-rate technology raises net returns by 1.1% (Schimmelpfennig 2016; Taylor 2018 p.17).

which about US$0.355 billion was in Asia / Pacific. Though this is very small compared to the global agricultural market value, the share has been growing.

Japan is one of the leading countries with respect to the development of vertical farming (Kozai 2013; Molin and Martin 2018). The number of vertical farming factories producing mainly lettuce had reached 35 in 2009 (Kozai 2013), and further increased to more than 150 in 2017 (Hayashi 2017; Molin and Martin 2018). In Japan, plant factory (植物工場) is one of the most application of vertical farming. While plant factories in Japan still focus largely on lettuce and not many other crops, as far as lettuce market is concerned, plant factories' production shares are estimated to have reached 13.8 percent in 2013, and likely to have been rising (Ogura 2017).

Notable examples in other countries include PlantLab in Holland, Grönska and Node Farm in Sweden, Sky Greens in Singapore, Green Spirit Farms, FarmedHere, The Plant, Green Girls Produce, Brooklyn Grange, and Gotham Greens in the United States (Al-Kodmany 2018).

In Egypt, Bustan Aquaponics, the first aquaponic farm in the country, was built in the mid-2010s (van der Heijden, Farrag, and Blom 2013). Some simpler versions of vertical hydroponic farming are also found in Mexico, which rely mostly on natural sunlight (de Anda and Shear 2017). In Gaza, a self-governing Palestinian territory, fish farms have been installed on the roofs and upper levels of existing urban structures, where entrepreneurs and the Food and Agriculture Organization of the United Nations (FAO) provided participants with the supplies and training (Somerville et al. 2014; Clarkin 2016).

Scale of operations. By nature, farms or factories using vertical farms and related technologies, use relatively small floor space (than typical field farms), although much larger in terms of operational scale. Here we provide a few examples whose information are provided. Their floor spaces are typically less than 0.5 ha (5000 m^2) (Table 12).

Table 12. Floor space of selected vertical farms

Vertical farms	Descriptions	Floor space (m^2)	References
Omega garden carousel (Canada)	Hydroponic power house	14	Despommier (2010)
Eagle Street Farm (United States)	Vegetable farm located on a three-story warehouse	557	Clarkin (2016)
Brooklyn Grange	Rooftop farm	3,700 (the world's largest rooftop garden)	Clarkin (2016), Al-Kodmany (2018)
Nuvege (Japan)		2787 - hydroponic facility 5295 - vertical grow-space	Al-Kodmany (2018)
Urban Farmers - UF001 LokDepot (Switzerland)	World's first aquaponic rooftop farm with commercial purpose	260 (Producing 5 tons of vegetables & 800kg fish per year)	Kotzen (2010)
Valcent Company (Canada)		370 – plants 186 – space for germinating, harvesting, and packing (overseen by 3 staffs)	Benke and Tomkins (2017)

Source: Authors' compilations from studies described in the table.

These vertical farms use a number of vertical farming equipment. In Singapore, Sky Greens 'A-Go-Gro' technology uses a number of vertical farming equipment called "A-frame tower" (or Frame Trellis – A-frame design)[9], which is illustrated in Figure 1, which could typically use 5.6 m^2 of floor space (Table 13), but can use 2.8 times more growing space due to the slope (Graff 2011 p.70, cited in Perez 2014). In Kranji, near Singapore's central business district, Sky Greens erected 120 towers and there are plans for an additional 300 to support the daily production of 2 tons of vegetables (Benke and Tomkins 2017). Sky Greens can produce one ton of fresh veggies every other day, and supply a variety of tropical vegetables including Chinese cabbage, Spinach, Lettuce, Xiao Bai Cai, Bayam, Kang Kong, Cai Xin, Gai Lan and Nai Bai (Benke and Tomkins 2017).

Table 13. Floor space of selected individual vertical farm machines

Vertical farms	Descriptions	Floor space (m^2)	References
Omega Garden (Canada)		5.65 m^2	Graff (2011); Perez (2014)
Sky Greens (Singapore)	Hydroponic power house	A-frame system – 5.6 m^2	Benke and Tomkins (2017)

Source: Authors' compilations from studies described in the table.

Figure 1. A-frame design tower used in vertical farming

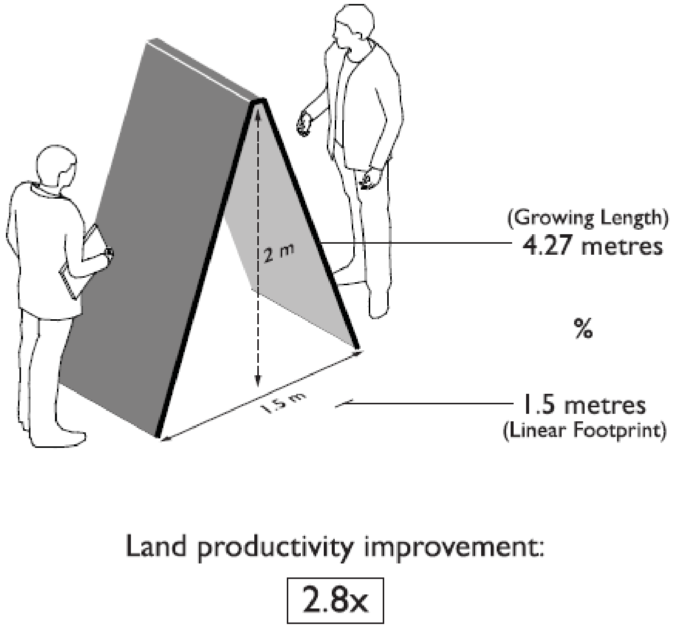

Figure 2.10 Space efficiency of the A-Frame design (Graff, 2011, p.70).

Source: Graff (2011 p.70); Perez (2014 p.50)

Among 45 plant factories surveyed in 2016, typical annual production revenues were 50 ~ 100 million yen (about US$0.5 ~ 1 million) (Ogura 2017). About 30 percent earned revenues between 10 ~ 50 million yen (US$0.1 ~ 0.5 million), while about 30 percent earned more than US$1 million (Ogura 2017) (Table 14).

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[9] Frame Trellis (also called "The A-frame "trellis") is typically used for hydroponics, and is the first commercially successful hydroponic system to exhibit a vertical orientation (Perez 2014 p.50). It has been the standard in the hydroponic industry for decades, although shading/light reduction per plant remains one of the challenges (Perez 2014 p.50).

Table 14. Annual sales revenues of surveyed plant factories in Japan, 2016 (N = 45)

Revenue bracket (million yen)	< 10	10 – 50	50 - 100	100 - 500	> 500	No sales
Share (%)	11.1	28.9	13.3	24.4	6.7	15.6

Source: Ogura (2017).

Facility of operations. Oftentimes, these vertical farm enterprises emerged through operations on existing office space or shipping containers. For example, Grönska in Sweden, which is the first to grow plants vertically and sell them on the market in Sweden, built its growing system in the basement of an existing office space (Bustamante 2018). Node Farm in Stockholm operates in an old refrigerated shipping container (Molin and Martin 2018). Freight Farms produces a “leafy green machine” that is a complete farm-to-table system outfitted with vertical hydroponics, light-emitting diode (LED) lighting and intuitive climate controls built within a 40’x8’ shipping container (Hamdan et al. 2016). OA Farms of Orix Group in Japan started fully artificial-light based plant factory using a building renovated out of a gym of an elementary school that had closed, to produce frill lettuce, Red Leaf Lettuce (Ogura 2017).

Crops grown. Generally limited range of crops have been grown with vertical farming, including mostly vegetables such as lettuce, strawberries, and tomatoes (Cox 2016 – cited in Benke and Tomkins 2017). Enterprise like Grönska in Sweden produce basil as main product (Bustamante 2018). In hydroponics, common crops grown include tilapia and lettuce (Somerville et al. 2014). Similarly, in aquaponics, leafy green herbs and vegetables are generally suitable, as well as large fruiting vegetables are also applicable, including tomatoes, peppers, eggplant, and cucumbers, peas and beans (Somerville et al. 2014). Root crops and tubers are less commonly grown and require special attention (Somerville et al. 2014). Frazier (2017) reports that a reason for leafy greens being very popular as a crop is that they provide a premium profit margin, rather than any inherent limitations in crop types (Benke and Tomkins 2017).

In Japan, while leafy lettuce is the most commonly grown crop in plant factory, productions have been gradually expanding to other crops, mostly functional vegetables, including Common Ice Plant, Glycyrrhiza, and low-Kalium vegetables (medicinal plants used for people with kidney problems) (Oguro 2014). Among 48 plant factories surveyed in 2016, about half (46%) grew leafy lettuce, about 20 % grew tomatoes, herbs, respectively, and about 10 % grew baby leaves and flowers (Ogura 2017).

Relatedly, according to Kozai (2013), plants suitable for artificial-light based plant factory generally include those that grow well under relatively low light intensity (about 200 μmol/m2/s) and high CO_2 (about 2000ppm), short production cycles (10 – 30 days between planting of seedlings to harvests), high plant density (as high as 50 ~ 500 per m^2), high proportion of salable parts (as much as 90% of entire plant), high values-to-weight ratios (more than 1000 yen / kg), functional components whose density can be controlled environmentally (light quality, temperature, moisture, air speed etc.), for which grains or beans are generally unsuitable.

Types of business entities entering vertical farming, plant factories. Many of the entities starting vertical farming, including plant factories, are non-farm enterprises. In Japan, various plant factories have been started by banks, universities, other companies in the business of real estate, trading houses, railway/transportation, medicines, retail industries, ceremonies, information and communication technologies (ICTs), paper industries, fibers / chemicals / steels, lighting / air conditioning, seeds / gardening, semi-conductors, law firms, among others (Kozai 2013). For example, Fujitsu, one of the major information technology (IT) firms in Japan, turned the free space at production facilities of semi-conductors into plant factories in Fukushima in 2013, not only to simply produce vegetables, but also a testing ground for the Big-Data based production management system that the company develops, through application to vegetable production (Ogura 2017).

4.2 Characteristics

4.2.1 Perceived benefits of vertical farming

Al-Kodmany (2018) summarizes the sustainable benefits for which vertical farming is perceived to be intended (Table 15). These are generally in line with what Despommier (2010 p.145-146) laid out earlier. One of the often-perceived benefits is the potentially significant reduction in water used for food production. The figures of 70-95% water saving potential (Despommier 2010) or 90% water saving potentials by aquaponics (Alderman 2015; Franchini 2016) are still widely referred in the literature. Reduced water use is also potentially enabled through water recovery, i.e., “water lost through transpiration and evaporation can be collected and thus reused (Ellis, 2012).” (Voss 2013), which may apply to protected agriculture in general. Similarly, plant nutrient efficiency may be higher in indoor aeroponic or aquaponics farming than in open fields, because virtually all the nutrients applied are captured by the plants (Pinstrup-Andersen 2018). Of course, there remain a number of economic hurdles toward fully exploiting the potential of vertical farming. However, these sets of perceived benefits emphasized in the literature suggest that, continued research to reduce the costs of vertical farming technologies should be encouraged where the social values of these benefits are high.

Table 15. Perceived benefits of vertical farming

#	Benefits	Environmental	Social	Economical
1	Reduce food-miles (travel distances)	Reduce air pollution	Improve air quality, health	Reduce energy, packaging, fuel use
2	Reduce water consumption for food production	Reduce surface water run-off	Make portable water available to more people	Reduce costs
3	Recycle organic waste	Reduce needed land fills	Improve food quality, purify grey water to drinking water	Turn waste into asset
4	Create local jobs	Reduce commuting time	Create a local community of workers and social network with farmers	Benefit local people economically
5	Reduce fertilizers, herbicides and pesticides	Improve the environmental well-being	More control of food safety	Reduce costs
6	Improve productivity	Needs less space	Reduce redundant, repetitive work	Offer greater yields
7	Avoid crop losses due to floods, droughts, hurricane, over exposure to sun, and seasonal changes	Reduce environmental damage	Improve food security	Avoid economics losses
8	Control product / produce regardless to seasons	Year-round production	Increase accessibility year-round	Stimulate economic activities year-round
9	Use renewable energy	Reduce fossil fuel use	Improve air quality	Reduce costs

#	Benefits	Environmental	Social	Economical
10	Bring nature closer to city	Increase bio-diversity	Improve health, reduce stress and improve welfare	Create jobs in the city
11	Promote high-tech and green industry	Improve environments	Encourage higher education and generated skills	Provide new jobs in engineering, biochemistry, biotechnology, construction and maintenance, R&D
12	Reduce the activities of traditional farming	Preserve and restore natural ecosystem	Improve health	Save money required to correct environmental damage
13	Repurpose dilapidated buildings	Enhance the environment	Create opportunities for social interaction	Revive economy

Source: Al-Kodmany (2018 Table 6)
Note: R&D = research and development.

4.2.2 Types of technologies involved / used

Vertical farming systems, both existing type and planned types, are characterized in various dimensions.

4.2.2.1 With or without combinations with protected agriculture

Exposed system with little climate control. For exposed systems, green walls and green roofs (rooftop farms) are some of the notable examples (Clarkin 2016). An example of a green roof is found in Greenhost Hotel, in Yogyakarta Indonesia (Suparwoko and Taufani 2017). In Indonesia, a green roof is also constructed on tilted or sloping roof (often used in Indonesia), not only on the flat roof (Suparwoko and Taufani 2017).

Indoor systems. Indoor systems are similar to the protected agriculture covered in the previous section, but more issues on lighting and nutrient supply apply to vertical farming, and affect the type of systems that are developed and adopted, as is described below.

4.2.2.2 Light

Vertical farming relies on either natural light, or artificial light, or both. In the systems that fully or partly rely on natural light, it has more implications on the architectural designs selected (and consequent overall costs) (Heath, Zhu, and Shao 2012). Specifically, building shapes are designed to optimize light reflecting /delivering structures, and an additional set of equipment are installed to further enhance access to light (light reflectors or light tubes/fibers). While this eventually reduces requirements for supplemental energy, more initial investments are needed to research architectural designs, solar radiation, and local weather conditions including solar altitude angle, temperature, wind velocity (Heath, Zhu, and Shao 2012).

Artificial light. An alternative is the increased reliance on artificial light. As the dependence on artificial light rises, initial costs become higher. For example, for 60 ha vertical farm, the initial costs can reach over $100 million (Heath, Zhu, and Shao 2012).

Incandescent (INC) bulbs are one form of artificial light, which is also often used in greenhouses (Perez 2014 p.39). In Japan, among 26 plant factories surveyed in 2016, 77% used

INC bulbs while less than half used LEDs (Ogura 2017). INC bulbs are generally inexpensive and emit an effective spectrum, but are often less energy efficient and require greater power availability (Perez 2014 p.39). An improvement in traditional INC includes compact fluorescent bulbs (CFLs). While CFLs are more energy efficient and usable for many crops, their spectrum cannot control flowering of some long-day plants, although CFLs may be suitable for a rapid flowering of some LD crops like pansy and petunia (Currey and Lopez 2013; Perez 2014 p.39).

A further alternative is LED. LED light has been used as the source of artificial light, originally modified to emit light with a wavelength that are suitable for plants (Despommier 2010 p.175). In Japan, the transition to LEDs started in 2005 (Kozai 2013) and is today the main source of lighting (Kozai, et al., 2013; Molin and Martin 2018). Because of its long lifespan, energy efficiency, and ability to target specific wavelengths of light, LED is a viable option for managing photoperiod (Perez 2014). LEDs also provide the opportunity to adjust the ratio of red (R) and far-red (FR) light for desired plant responses, which can promote stem elongation in many plant species. (Perez 2014). Blue LED light can help to shorten the plant height, which can facilitate transport when needed (Lu 2016). LEDs are low in radiant heat and can therefore be placed near the growing plant, thus more suitable for vertical farms with narrow height shelves. Significant development of LED has enabled vertical farms to be a more nature-independent entity (Heath, Zhu, and Shao 2012); With a high-electricity-to-light conversion efficiency, this artificial lighting can replace natural sunlight as the energy for plants' growth.[10]

There is still scope for further improving the efficiency of LEDs. Currently, available LED technologies provide only 28% efficiency, which needs to be increased to about 50-60% (Al-Kodmany 2018).

Other technologies to improve lighting efficiency. Other technologies are added as well, depending on the added benefits and costs of installations. Sunlight reflecting, collecting, and delivering devices, such as light shelves, light pipes, fiber optics, are sometimes used to penetrate natural light deep into buildings to provide energy for plants' photosynthesis (Heath, Zhu, and Shao 2012). For covering materials, improved materials like ETFE (Ethyl Tetra Fluoro Ethylene) – a light, flexible and self-cleaning material that has very high transparency (95% visible light transmission) and good thermal properties, are also used where profitable, although the feasibility of ETFE in a high-rise environment can be subject to various other factors, including high wind speeds) (Heath, Zhu, and Shao 2012). Research is also on-going, regarding how to increase crop yields by using optimized production methods, such as light exposure variations (Hamdan et al. 2016).

Rotating technologies.[11] Rotating the platform is often used as well from lighting purpose. For example, Sky Greens in Singapore uses the aforementioned "A-shaped towers", which consist of up to 26 tiers of growing levels (Benke and Tomkins 2017). These tiers rotate at one mm per second to provide uniform solar radiation (Benke and Tomkins 2017; Krishnamurthy 2014). Similarly, Valcent Company in Canada uses multi-level stacked plastic trays in a climate-controlled glasshouse enclosure, which are rotatable mechanically and provide uniform solar exposure (Benke and Tomkins 2017). The troughs slowly rotate around the aluminum frame

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[10] LED has also been further modified to improve its suitability. For example, organo-light-emitting diodes (OLED), which is light-emitting organic compounds spread out on thin films of plastic, allows greater control of the wavelengths of light, and thus suitable for plants. In Netherlands, modifying colors of LED are found to reduce energy consumption, and double the efficiency of photosynthesis (Heath, Zhu, and Shao 2012).

[11] Rotation is also sometimes used for other purposes than lighting. For example, in Omega garden carousel, rotation is used to develop oils in the plants which enable faster growth rates and better taste (Despommier 2010 p.173).

(about three rotations per day) to ensure that the plants obtain uniform sunlight. A similar rotating method is also used for the vertical farming building, such as in as sunlight is allowed into the building throughout the day from all directions inside crop surfaces, as used in Experimental Vertical Farm in Chile (Matharu 2016).

Rotating technologies are also combined with artificial lighting. For example, in Omega garden carousel in Canada, stacked drums are used, which consists of growing plants within the interior of a drum structure positioned around a central artificial light source (Despommier 2010; Perez 2014).

4.2.2.3 Growing medium and nutrient / water supply

The increased use of non-soil materials as a growing medium is an important element of vertical farming. Such non-soil medium has also been used in protected agriculture, as described above, but it is more important for vertical farming in which more production takes place far away from the ground where the soil is naturally placed. The plant growing medium is an important consideration for the success of vertical farms as well as living walls and as aquaponics systems do not normally use soil-based growing media, this study investigates various types of growing media that can be best used in vertical aquaponics (Khandaker and Kotzen 2018).

There are various methods for achieving soil-less production. For example, Rooflite soil has been increasingly used, which is a lightweight soil composed of organic matter compost and small porous stones which break down to add trace minerals that are needed for the produce to grow into a healthy and mature state (Al-Kodmany 2018). Brooklyn Grange in New York grows plants in 19 cm (7.5 in) deep beds with Rooflite soil (Al-Kodmany 2018).

Soil-less medium is also often used with *hydroponics* (Khandaker and Kotzen 2018). Three main methods are used with a particular case of hydroponics; (1) media beds; (2) nutrient film technique (NFT); (3) deep flowing techniques (DFT) (also called deep water culture) (Somerville et al. 2014).

Media beds are most popular for home gardeners, as they are easiest to build and maintain (Bernstein 2014 cited in Alderman 2015). However, media beds have downsides. Harvesting whole plants can be difficult because plant roots often become entangled in the media, and while large plants like tomatoes require the structure and high nutrient profile available in media beds, crops like lettuce are easiest grown in other systems (Bernstein 2014; Alderman 2015).

NFT have also been used in vertical farming and hydroponics. NFT is constructed of small pipes that run horizontally with holes every foot or so that plants are planted into (Alderman 2015). NFT is, however, generally suited for small plants that have a low nutrient requirement such as lettuces (Bernstein 2014; Alderman 2015).

DFT uses large volumes of water pumped from fish aquariums into long troughs that are kept at a constant level and plants are suspended above the water, usually in Styrofoam rafts with the root systems dangling down into the water absorbing nutrients (Alderman 2015). It can produce large volumes of plants in a relatively small space and ease of harvest due to the roots not clinging to anything (Bernstein 2014; Alderman 2015). DFT differs from NFT, in a way that the plants are suspended in a sloping bed so that the water flows slowly through the root system, from a high to low; resulting in a reduced water level (ibid.) (Lu 2016; Molin and Martin 2018).

Some of other common “substrates” (through which roots grow and penetrate) used include horticultural grade coconut fibre and horticultural grade mineral wool (Khandaker and Kotzen 2018).

Hydroponics or aquaponics can be further made efficient by combining vertical living wall (Khandaker and Kotzen 2018). In traditional aquaponics, the ratio between fish tanks, filters, and plant tanks is typically 2:1:5, so that plant tanks occupy close to half of the production space. Combining with vertical wall can reduce space, and achieve higher productivity (Khandaker and Kotzen 2018).

There are also research on-going for a few alternative ways to provide nutrients to plants, including Ultrasonic foggers, GrowCube, and Solar Aquaculture (detailed are provided in Al-Kodmany 2018).

Water supply in water-scarce environment. For indoor farming in water-scarce areas, aeroponics can be used for supplying water to plants. Aeroponics is the application of a fine mist of water laden with plant nutrients onto the root system of a given crop, for example, spinach (Despommier 2010). Aeroponics is believed to reduce water requirements by up to 70% compared to hydroponic technologies (Despommier 2010; Voss 2013).

4.2.2.4 Other more advanced features

Electricity generation facilities. Some of the modern, futuristic types have integrated electricity generation facilities through wind – 200 – 600 kWh / year (Franchini 2016). These types, however, also incur millions of dollars of operating costs per year.

Integration of production scape to offices, residential space. Some of the more forward-looking research focuses on designs that fit directly into the urban areas (like Shanghai) where most of the plots in the inner-cities and city centres are already occupied with buildings (Januszkiewicz and Jarmusz 2017). In such designs, buildings are structured such that vertical farms are built on top of the traditional cities. Another area that is attracting attention in research is the technologies to expand the functions of vertical farm buildings, for example through the accommodation of office space, and residential spaces, or mixed-use skyscrapers which incorporates a personal or communal planting space as per the needs of the individual, instead of the wholesale production for marketing (Hamdan et al. 2016).

Some of the key technologies required for these systems are those that can control oxygen and CO_2 levels inside the building. Indoor farming usually supplies CO_2 levels to 3-4 times the rate normally found in the atmosphere (Heath, Zhu, and Shao 2012). One experimental example is Experimental Vertical Farm called Claudio Palavecino Llanos 2009 in Chile (Matharu 2016 p.29).

Water treatment. Research also looks into treatment of water within the vertical farming building. Using rainwater (collected from the top of the building) and wastewater (through waste treatment plant) from the building can be potentially utilized as a water system that will be used for hydroponic plants (Putri, Sharfina, and Prakarti 2015). Wastewater management can potentially be done using a tank-based system traditionally housed within a greenhouse or a combination of exterior constructed wetlands with Aquatic Cells inside of a greenhouse (Todd 2012; Perez 2014). The system often includes an anaerobic pre-treatment component, flow equalization, aerobic tanks as the primary treatment approach followed by a final polishing step through Ecological Fluidized Beds or a small constructed wetland, which can obtain high-quality water without the need for hazardous chemicals (Todd 2012; Perez 2014). "The water vapor that evaporates off the plant has effectively been cleansed of any remaining pollutants it may have contained. By simply dehumidifying the indoor air one could recollect the massive amounts of water transpired by the plants inside a vertical farm, taking advantage of natural means of water purification (Despommier, 2010a).” (Voss 2013). “Plants used in this purpose would not be suitable for eating. Therefore, these buildings would have to act as separate standalone vertical farms devoted entirely to the purpose of water purification. Instead, biomass produced in these buildings could be used in biofuel production adding an additional cost benefit to the solution.” (Voss 2013).

4.3 Economics of vertical farming

Information on costs of vertical farming technologies is still largely limited and little information exists from actual production establishments (Pinstrup-Andersen 2018).

4.3.1 Key cost components in vertical farming

Vertical farming, especially of the more modern types, is highly capital intensive and costly. Key cost items include energy use, particularly for providing artificial light to supplement natural sunlight. In Japan, Kozai (2013) indicated that, production costs at plant factories generally consist of capital depreciation costs (30 – 35% of total costs), labor costs (20 – 25%), utilities like lighting, heating, and water (25- 30%), and others.

Energy costs. One of the main obstacles for vertical farms is the costs of building a lighting system, and the energy consumption to run it (Shimizu et al. 2011; Molin and Martin 2018), which can sometimes account for 70-80 % of the total electricity costs used. It is typically found that vertical farms require more energy than greenhouses mainly due to lighting (Graamans et al. 2018; Molin and Martin 2018). Plants generally require lighting for 16 to 18 hours a day when they are not receiving sufficient sunlight (Massa et al. 2008; Clarkin 2016). While LED lights are continued to be improved, in order for vertical farms to be more viable, LED lighting must be made more energy efficient (Despommier 2010; Clarkin 2016). In Indiana, the United States, electrical energy requirements for LEDs for growing lettuces are estimated to be 17.5 kWh / kg of lettuce (if 100% dependent on artificial light), approximately 2068 kWh / m^2 / year (Perez 2014). For a hydroponic plant, the average energy consumption has been estimated to be between 14-17 kWh/m^2 (Xydis, Liaros, and Botsis 2017; cited in Molin and Martin 2018), depending on the layout of the structure.

Because of these, it should be recognized that, there are still many critics who question the viability of vertical farming in the foreseeable future. The production costs, in terms of energy use and greenhouse gas (GHG) emissions, for vertical farming may end up too high when natural sunlight is removed from the equation (Hamm 2015; Molin and Martin 2018).

Land. Secondly, despite land-saving benefits that vertical farming brings, land often remains some of the large cost items (Voss 2013). This is because, vertical farming is often more suitable in urban areas where land price is also high, especially if the land is purchased in central business districts (Benke and Tomkins 2017).

4.3.2 Profitability

A significant share of existing vertical farming business, including plant factories, are subsidized by the government. Consequently, a significant share of them incur net losses, especially at early stages of their business growth. Among more than 100 plant factories in Japan, about 20 percent realized positive operating profit, about 60 percent realized break-even, and 20 percent incurred net losses in 2013, although the share of positive profits had been rising gradually (Kozai 2013). Higher profits are also generally positively associated with greater production scale. Among lettuce plant factories in Japan, those realizing net profits were typically with production scales of 1,000 ~ 1,500 units / day (Kozai 2013). One plant factory in Japan in Kameoka, called Spread, realized 8% operating profit in 2013, but only after incurring net losses for 6 straight years since the entry into business in 2007 (Ogura 2017). A survey of 70 construction companies in Japan, which entered into agricultural sector, including plant factories, revealed that, typically, 7 ~ 8 years had been needed before the business turned from net losses into net gains (Ogura 2017).

4.3.3 Examples of production budget

Small-scale aquaponics. Somerville et al. (2014 Appendix 7) describes typical costs and profit structures of a small-scale aquaponics system. The example by Somerville et al. (2014 Appendix 7) is for production capacity of a small-scale media bed unit with 3 m^2 of growing space and 1-000 litres of fish tank space, producing 360 heads of lettuce and 54 kg of tomatoes per m^2 per year, and 30 kg of fish (tilapia) per year (Table 16).

Table 16. Revenues

Products	Production (quantity)	Revenue (US$)
Lettuce	360 head	432
Tomatoes	54 kg	86.4
Fish	30 kg	240
Total		758.4

Source: Somerville et al. (2014 Appendix 7, Table A7.2).

Table 17 summarizes the total capital costs for a media bed unit, for this facility. The total capital costs amount to approximately about US$700. Table 18 summarizes the operating costs, which is estimated to be approximately US$26.45 / month, or US$317.40 / year. Lastly, Table 19 summarizes the revenues, costs and profits. For 1000 litre tank and 3 m^2 growing space, these figures re-confirm the capital-intensive nature of vertical farming.

Table 17. Total capital costs for a media bed unit (1000 litre fish tank and 3 m^2 growing space)

Item description	Price (US$)
IBC tanks	200
Electrical equipment: water pump, air pump and connections	120
Media bed support: concrete blocks and wood planks	80
Volcanic gravel (biofiltration medium)	120
Miscellaneous items: Fish net, plumber's tape (Teflon), shading materials etc.	100
Plumbing: pipe fittings and connections	80
Total	700

Source: Somerville et al. (2014 Appendix 7, Table A7.1).

Note : IBC = intermediate bulk container.

Table 18. Total monthly operating cost for running a small-scale aquaponic unit

System inputs	Unit	Units per month	Price per unit (US$)	Total cost (US$)
Plants	Seedling	35	0.10	3.50
Fish	Fingerling	5	1.00	5.00
Electricity	kWh	25	0.10	2.50
Water	Litre	450	0.0027	1.20
Fish feed	Kg	4.5	2.50	11.25
Miscellaneous		1	3.00	3.00
Total costs / month				26.45

Source: Somerville et al. (2014 Appendix 7, Table A7.2)

Table 19. Annual cost-benefit analysis of a media bed unit

Total costs per year	
Initial construction costs	700.00
Yearly operating costs	317.40
Yearly revenues	758.40
Yearly net profit	440.00
Payback of initial construction costs (months)	19

Source: Somerville et al. (2014 Appendix 7, Table A7.4)

Vertical farming for onion in the Philippines. The second example is vertical farming for onion production in the Philippines studied through experiment methods by Pascual, Lorenzo, and Gabriel (2018). The production scale of focus in this case is (Pascual, Lorenzo, and Gabriel 2018 Figure 9.2):

- 9-m, diamond-shaped structure consisting of 30 tiers of troughs made up of 7.6-cm-diameter, 2.5-m-long PVC pipes
- Water is supplied at the upper-middle trough from an overhead tank, 9.2 m high and circulated through each pipe and then drains at the lower-middle channel
- The pipe that connects each trough is a flexible hose so that it will conform to the A-shape of the frame as the troughs rotate. Each trough contains 25 onion bulbs spaced at 10cm apart. The frame has a foot area of 2.5 m × 2 m (5 m^2). A 1500 m^2 lot area could contain 200 racks and would produce 15,000 kg of onion almost equivalent to 1 hectare of traditional farming unaffected by any adverse weather and growing conditions.
- If using the traditional production method, the entire 10,000 m^2 farmland area was used while in the vertical hydroponic farming system, the remaining lot space could be used for other agricultural and live stocks production.

With this level of production scale, the production costs under hydroponic system are estimated as in Table 20.

Table 20. Hypothetical costs per hectare of onion using hydroponics in the Philippines

Items	Vertical hydroponic farming (2500 m^2 land area) Useful life of item 1:20 years Loan \$60,000
Year 1, 1st cropping	
1. Initial cost (equipment and accessories)	44152
1. Operational expenditures	
Seedling preparation	877
Variable cost	336
Loan (fixed interest @ 24% per annum)	4800
Loan capital deducted	2000
2. Total operation expenditures	8010
3. Total expenditures	52162
4. Projected yield per ha / cropping	16680
5. Projected income per cropping (projected yield – operational expenditures)	8670
6. Remaining balance (considering a loan payable in 10 years with 24% interest per annum)	7838
7. Total remaining balance	16607
Year 1, 2nd cropping	
1. Initial investment	16607
2. Total operational expenditures	8010
3. Projected yield per ha / cropping	16680
4. Projected income per cropping	8670
Remaining balance	25277
Year 1, 3rd cropping	
1. Initial investment	25277
2. Total operational expenditures	8010
3. Projected yield per ha / cropping	16680
4. Projected income per cropping	8670
Remaining balance	33946

Source: Pascual, Lorenzo, and Gabriel 2018.
Note: ha = hectares.

Japanese firm Mirai (Perez 2014p.46; Benke and Tomkins 2017). The third example is a vertical farming firm in Japan called Mira. Their production capacity is 300 lettuce heads / day for 60 m^2, or 10000 lettuce heads / day for 1200 m^2. The firm invests significantly in hygiene, which is key to prevent pathogens in the facility and prevent diseases to affect the crops, including air cleaning (filtering) system, lab suit, Air shower for workers before entering, and water shower prior to access for complete removal of pathogens in large-scale facilities. (Shimamura 2012, p.5; Perez 2014). Table 21 summarizes the technological specifications.

Table 21. Technological specifications of indoor lettuce production through vertical farming by Mirai, a firm in Japan

Categories	Descriptions
Building size (modular building)	1300m^2 (14000 ft^2) footprint (1100m^2 or 12000 ft^2 footprint for 4536 m^2 production area)
Crop	Leafy lettuce (10080 heads per day, 100 g per head)
Nutrient delivery and lighting systems	NFT Combination of LEDs and white fluorescent lamps
Other facilities	Office space, packing area, storage, cold storage (200 m^2)
Other equipment	Cooling / heating, seedling production systems, irrigation tanks and injection systems, climate controller etc
Equipment / facility life	Production systems for 7 years; 15 years for other equipment; 20 years for the building

Source: Perez (2014 p.48).
Note : LED = light-emitting diode ; NFT = nutrient film technique.

With this level of production capacity and technological specification, total revenue and production costs per year are estimated at US$4.1 million and US$3.4 million, respectively (Table 22). Required capital costs are in the order of approximately US$6 million, consisting of equipment and facilities (51%), building (31%) and construction costs (19%) (Table 23). The annual operating costs of US$3.4 million can be categorized into salaries and wages (26%), utilities (26%), capital depreciation costs (22%), materials (6%), transportation and shipping (2%) and other costs (18%) (Table 24).

Table 22. Balance estimate

Items	Income / expense	Note
Annual gross sales	$ 4.1 million	$ 5.68 / lb (10% production loss)
Annual costs (total)	$ 3.4 million	$ 4.7 / lb

Source: Perez (2014).

Table 23. Capital costs

Items	Costs	Notes
Building	180 M yen (31%)	New construction
Construction	110 M yen (19%)	Utility set up
Equipment and facilities	300 M yen (51%)	NFT systems, irrigation systems, lighting systems, others

Source: Perez (2014).
Note: NFT = nutrient film technique.

Table 24. Annual operating costs of US$3.4 million

Items	Costs	Note
Salaries and wages	71.3M yen (26%)	Two full time workers + hourly laborers (210 h / day, $10 / h)
Materials	15.4M yen (6%)	Packing materials, seeds, light bulbs, fertilizers, chemicals
Utilities	72.6 M yen (26%)	369 MW / month power use + water use
Transportation and shipping	6.0 M yen (2%)	
Other costs	49.2 M yen (18%)	Facility / equipment maintenance, consulting
Depreciation	59.2 M yen (22%)	

Source: Perez (2014).

5 Conclusions

In this paper, we briefly reviewed the issues for three selected frontier technologies; protected agriculture, precision agriculture, and vertical farming. We systematically checked the academic papers which have been written on these technologies and have been listed in Google Scholar. The body of literature on these three technologies, especially protected agriculture and (to some extent) precision agriculture, is vast and many of which are beyond the scope of this paper. To keep the scope of the review more relevant to India, we narrowed our search to articles that specifically include the names of developing countries in Asia in the titles. Where appropriate, a few widely-cited overview papers for each technology is also reviewed. The paper generally reveals where there are potentials to raise the performance of these technologies in developing countries like India, based on the general trends in the literature.

For protected agriculture, recent research has focused on, among others, tunnel heights, covering materials, shading structures, types of climate parameters controlled, frames and sizes, and energy structures. For precision agriculture, recent research has focused on the spatial variability of production environments, development of efficient and suitable data management systems, efficiency of various types of image analyses and optical sensing, efficiency of sensors and related technologies, designs of precision agriculture equipment, optimal inputs and service uses and their spatial allocations, potentials of UAV and nano-technologies. For vertical farming, research has often highlighted the variations in technologies based on out-door / indoor systems, ways to improve plants' access to light (natural or artificial), growing medium and nutrient / water supply, advanced features like electricity generation and integration of production space into office / residential space, and water treatment methods. For low-income South-Asian countries like India, these may be some of the key areas that the country can draw on from other more advanced countries in Asia, or focus in investing further research to improve the relevance of the technologies for the country.

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New Delhi 110012 India
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