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Is vertical farming a relevant and feasible solution for sustainable agriculture among smallholders in South Asia?

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Declaration regarding AI tool usage in this master's thesis

During the preparation of this master's thesis, we utilized ChatGPT for the following purpose:

1. As a spelling and grammar review tool, to generate synonyms and help with French-English translation.

2. After using ChatGPT, we diligently reviewed and edited the content produced by the tool. We take full responsibility for the final content presented in this thesis.

By signing this declaration, we affirm that the content of this master's thesis reflects our original work, augmented by the responsible use of AI.

Done on August 7th, 2024, in Ottignies

Writing this thesis has been a challenging journey, and I could not have overcome it without the invaluable support of several key individuals.

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1. Introduction

Modern agriculture is currently facing two major challenges: on the one hand, the need to feed an ever-growing population and on the other hand, the imperative to limit its environmental impact. The latest projections by the United Nations indicate that by 2050, global population will increase to an estimated 9.7 billion and by 2100, to an estimated 10.4 billion (United Nations, 2022), and that most of this anticipated growth is expected to take place in the Global South, specifically Asia and Africa (Jain et al., 2023; Triodos Bank, 2019). As such, a 60-110% increase in food production (from its 2005 level) will be needed by 2050 to meet the rising demand (Cui et al., 2018).

But achieving this goal is contingent upon the sustainable development of agriculture, which constitutes the second challenge. The agriculture sector plays indeed an ambivalent role as it both contributes to climate change and is affected by it (Roy & George K, 2020). The agricultural system alone is responsible for more than one-fifth of global greenhouse gas emissions (Jain et al., 2023), due to intensive practices such as land clearing and the consumption of fossil fuels for vehicles and agricultural machinery (Agrimonti et al., 2020). Alongside this, modern agriculture uses 70% of global freshwater withdrawals (Jain et al., 2023), is to blame for deforestation and biodiversity loss, and is among the leading causes of water, air and soil pollution because of the abusive use of pesticides (FAO, 2014).

Yet, the agricultural system is bearing the full brunt of the consequences of global warming. Increasing temperatures cause abiotic stresses that adversely affect crop quality (Agrimonti et al., 2020). Events such as droughts, heatwaves, floods and other extreme weather conditions have a direct impact on agricultural yields and can lead to crop losses and soil depletion (Flourens, 2021). Besides these environmental stresses for plants, other biological stresses such as pests, diseases and pathogens result in significant loss of yield and quality (Chen et al., 2023). The frequency and severity of these factors are exacerbated by global warming (Trębicki et al., 2015). The Food and Agriculture Organization (2021) approximated that an annual loss of 40% in crop productivity occurs as a result of these combined factors. Furthermore, arable land is projected to decrease by approximately 50 million hectares by 2050 (Abbasi et al., 2022).

Therefore, we can assert that modern agriculture is actually confronted with three major challenges: the need for an increase in production quantity to meet the rising demand for food (intensification), in a way that utilizes minimal inputs and minimizes adverse environmental impacts (mitigation) (Jain et al., 2023; Roper et al., 2021; Trivelli et al., 2019), and by reducing the vulnerability of the sector to the effects of climate change (adaptation) (Agrimonti et al., 2020; Roy & George K, 2020).

How might these challenges be addressed?

Our minds tend to picture large-scale, industrialised and western big farms when thinking of the role of agriculture in feeding an ever-growing population. However, these farms represent just one facet of the agricultural landscape, the individuals responsible for feeding us and where those reside. Investing our efforts in those giants may not necessarily be the ultimate solution.

Instead, the key units to focus on may well be smallholder farms. Smallholder farms indeed constitute the dominant form of farming in most countries, accounting for more than 8 out of 10 farms worldwide (Lowder et al., 2016). They are the ones who will be called upon to produce a significant share of the additional 60-110% of food required to sustain the world's population by 2050 (FAO, 2014). They are also the ones particularly vulnerable to climate change and who will play a leading role in advancing food security and sustainability efforts (Cui et al., 2018). Thus, "*empowering smallholder farmers with enhanced management technologies to help them attain greater productivity and environmental performance is critical as we pursue an equitable world with a sustainable future*." (Cui et al., 2018, p. 366).

Helping them achieving intensification, mitigation and adaptation in agriculture will require both non-technological (insurance, social community, etc.) and technological (such as advanced farming technologies) solutions (Aryal et al., 2019).

An innovative method, commonly referred to as vertical farming (VF), has gained momentum globally and shows promise as an effective means to tackle those mentioned challenges, thanks to its potential for increasing food production, maintaining food security and fostering sustainable agriculture (Kabir et al., 2023; Mohapatra et al., 2023; Yeşil & Tatar, 2020). Its ability to grow crops in vertically stacked shelves under controlled environment is reshaping traditional agriculture (Kabir et al., 2023). High yields, continuous year-round production, minimized or eliminated reliance on pesticides or herbicides, water efficiency and improved resilience to the impacts of climate change are some of the claimed benefits of vertical farms (Benke & Tomkins, 2017).

Therefore, it is worth investigating whether the system of vertical farming could be a feasible and sustainable solution for agriculture among smallholder farmers. This is especially interesting for regions experiencing water stress or scarcity and that are extremely vulnerable to climate change (Bunge et al., 2022; Stein, 2021), such as South Asia (SA).

On this backdrop, this thesis examines the following research question: *Is vertical farming a relevant and feasible solution for sustainable agriculture among smallholders in South Asia?* For this study, SA includes Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan, and Sri Lanka.

The rest of the thesis is organized as follows. Section 2 focuses on smallholder farmers and starts by attempting to define them, before describing their prevalence in the current agricultural system, the issues they face and why they are a relevant population to focus on. Section 3 presents the concept of vertical farming by giving a definition, exploring its history and its current applications, with a due focus on its economic, societal and environmental benefits as well as its existing barriers. The conditions for successful development of vertical farming are also covered. These two sections constitute the theoretical part of this thesis, the aim of which is to highlight existing knowledge on the topic.

This theoretical groundwork will pave the way for the empirical part, which aims to assess South Asia's position concerning the feasibility of implementing vertical farm systems and their sustainability potential in their application, using synthetic indices. This empirical part is divided into three sections: section 4 outlines the research methodology, followed by the presentation of the findings in section 5, while section 6 interprets the results considering the insights gained from the literature review.

The final section of this thesis presents the main contributions and limits of this research. Some suggestions for future research will also be made.

PART 1 – LITERATURE REVIEW

2. Smallholder farmers

2.1. What is a smallholder farm?

There is no consensus or unique definition of a smallholder farm (or small farm) in the literature (Cohn et al., 2017; FAO, 2015). The term sometimes refers to family farms, subsistence or near-subsistence smallholders, resource-poor or low-technology farming (Hambye, 2021). The definition of what a smallholder farmer represents varies greatly depending on the geographical location and the scale of farming systems (Nyambo et al., 2019).

The size of the land is the most used criterion to classify farmers. A strong majority of the literature indeed defines smallholder farmers by their farm's physical size, primarily in terms of hectares of operated land (Aida Khalil et al., 2017). Using this criterion, Lowder et al. (2016) suggest that farm holders farming less than two hectares can be considered small. However, the scale differs considerably from one country to another, depending on agroecological as well as socio-economic considerations (FAO, 2015). What is considered small in most countries in the Caribbean and in Latin America is seen as large in most nations in Sub-Saharan Africa or Asia (Lowder et al., 2016).

This has led some authors to use identifiers other than land area to define smallholder farms. Some of these identifiers include the economic size of the farm, the percentage of production consumed on-farm, the quantity of economic output (Cohn et al., 2017), exposure to risk, harvesting techniques (Bread for the world, 2023), the quantity of inputs, demographic data, the labour availability or the usage of fertilizer (Nyambo et al., 2019). Aida Khalil et al. (2017, p.10) have grouped the definitions based on such a single criterion into the following 4 categories:

1) *The endowment of factors of production such as land, labour, technology.*
2) *The type of management of the holding - notably the degree of involvement of the family.*
3) *The connection between the farm and the market (market orientation).*
4) *The economic size of the holding.*

The second category calls for a definition of what can be described as a family farm, which must be distinguished from small farms. Although it is common to use the terms family farm and small farm interchangeably, differences exist between the two concepts (Hambye, 2021). A farm is qualified as a family farm if a member of the household owns or manages the farm and a minimum amount of labour is delivered by the owner itself or by his/her relatives (Aida Khalil et al., 2017). The family and the farm are interconnected, co-evolving as they integrate economic, environmental, reproductive, social, and cultural functions (Garner & de la O Campos, 2014).

As this definition does not imply a land size threshold, a family farm can be a large farm of more than 2 hectares. Hence, according to Matthews (2013), not all family farms are small farms but conversely all small farms are family farms. Nevertheless, there is a certain overlap between the two concepts. In practical terms, it is estimated that more than 90% of the world's farms can be considered as family farms, while small farms (less than 2 ha) account for 84% (Lowder et al., 2016).

Another distinction must be drawn between the terms small farm and subsistence farm. Subsistence or near-subsistence smallholders are those producing essentially for their own consumption, who have small or no market surplus potential (FAO, 2014) and who earn a large proportion of their income from sources other than agriculture (Aida Khalil et al., 2017).

The Food and Agriculture Organization of the United Nations (2014) summarised these differences by proposing a classification of farms based on their relation to markets and their capacity to innovate. The three categories are: subsistence and near-subsistence smallholders (who consume most of their production and with very few capacities to generate surplus production for the market), small farms (who either manage to generate a surplus for the market, whether local, national or international, or have the potential to enter the market) and large farms (who display characteristics of industrial ventures).

To clarify what has been discussed, let us examine three general definitions found in the literature on smallholder farming:

> *"Smallholdings are those farms with a low asset base and operating in less than 2 hectares of cropland."* (World Bank, 2003, p. 6)

> *"Smallholders are farmers operating under structural constraints such as access to sub-optimal amounts of resources, technology and markets."* (Aida Khalil et al., 2017, p. 7)

> *"Generally, a smallholder farmer is viewed as a person involved in farming a small piece of land, cultivating food crops, sometimes with small varieties of cash crops, and typically living in rural areas."* (Nyambo et al., 2019, p. 1)

Considering these definitions, it becomes evident that there is no unique definition of smallholder farms. The notion remains imprecise, although certain shared characteristics, such as market access, average land size and the labour supply, do emerge. This has implications for estimates of the number of small farms and the extent to which they contribute to food production, since it varies according to the chosen definition. Finally, it is worth mentioning that it is not always clear whether the tiniest of farms (sometimes referred to as marginal farms) are included in estimates or definitions of smallholder farms (Cohn et al., 2017).

2.2. The importance of small farms in food production…

In the context of this thesis, we will retain the criterion of size to define smallholder farms. Using the two-hectare threshold, it is estimated that the number of small farms is approximately 475 million (Lowder et al., 2016), i.e. 83% of the total (570 million) farms worldwide[1] (FAO, 2014). This confirms that smallholder farms form the backbone of agriculture.

Smallholder farms not only constitute the largest proportion of farms in the world, but they also produce up to 70% of all food consumed on this planet (Fanzo, 2017; Triodos Bank, 2019). The FAO (2015) specifies that in Asia and in sub-Saharan Africa (SSA), around 80% of all food is produced by small-scale farmers. And while these small farmers make up only 12% (289 million ha) of the world's farmland, over 2 billion people rely on them for their livelihoods.

The importance of smallholder farms is especially marked in low-income countries (Gomez Y Paloma et al., 2020). In the Global South, two-thirds of the rural population is employed by smallholder farms (Jain et al., 2023). Small farms also represent a significant part of the overall economy in emerging countries. In SSA for example, between 2007 and 2017, they contributed to 18-25% of the gross domestic product (GDP) (AGRA, 2016).

Additionally, the significance of small farms in biodiversity conservation and the adoption of sustainable practices within the food sector cannot be overstated. They contribute greatly to maintaining the genetic diversity of our food supply, in contrast to large-scale farms that often

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[1] See breakdown and geographic distribution of farms by size in Appendix 1 and 2.

produce standardized products and rely on monoculture (Fanzo, 2017). Small farms also demonstrate a heightened awareness of the local ecosystem, a deep understanding of land capabilities and actively engage in preserving fertile lands (Cohn et al., 2017).

So, representing more than eight out of ten farms in the world, producing up to 70% of food and occupying about 30-40% of land in low- and lower-middle-income countries (Lowder et al., 2016), it can definitely be argued that smallholder farms are essentials to our global food system.

2.3. … in South Asia

The role of smallholder farms is particularly crucial in South Asia.

Of the world's 570 million farms worldwide, almost 75% are located in Asia[2]. More precisely, China and India collectively account for 59% (respectively 35% and 24%). Another 9% is attributed to other countries in East Asia and the Pacific, 6% take place in other South Asian countries nations. Sub-Saharan Africa hosts only 9% of the world's farms, while Europe and Central Asia account for 7%, Latin America and the Caribbean for 4%, and high-income countries for the remaining 4% (FAO, 2014).

This means that South Asia, composed of Bangladesh, Afghanistan, Bhutan, India, Nepal, Pakistan, Maldives and Sri Lanka, is home to 30% of all farms. Of these 30%, about 70–80% are smaller than 2 ha and operate about 30–40% of land (Lowder et al., 2016). Moreover, it is worth mentioning that in South Asia, the number of small farms is still increasing meanwhile the average farm size is shrinking (Gomez Y Paloma et al., 2020).

2.4. Why targeting smallholder farms in South Asia?

The biggest challenges will arise in countries where smallholders dominate the farming landscape, such as in South Asia (Cui et al., 2018). As the major agricultural participants, smallholder farmers are called on to produce most of the additional 60% of food needed to feed the population by 2050 (FAO, 2014). At the same time, small farms will have to play a key role in the ongoing fight against poverty, hunger and the degradation of the natural environment. Achieving sustainability and food security will depend on how smallholders farm their land (Cui et al., 2018) and how they adapt to climate change.

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[2] See breakdown in Appendix 3.

2.4.1. Supporting the growing demand for food and the fight against poverty and hunger

Most of the growth will take place in the less developed countries, which are expected to double in terms of population, from around 900 million in 2013 to 1.8 billion in 2050 (Nations Unies, n.d.). This is critical as it means that most increases in food demand will occur in these countries, specifically South Asia and Africa (Jain et al., 2023), leaving small farmers with a significant challenge, as they produce around 80% of the food in these regions.

In addition, and as already mentioned above, while more than 2 billion people depend on smallholder agriculture for their livelihoods, small farmers represent the poorest and hungriest people in the world (Triodos Bank, 2019). Individuals engaged in small-scale food production, including farmers but also fishers, herders, etc., constitute half of the global undernourished population and the majority of those living in extreme poverty (IFPRI (International Food Policy Research Institute), 2005). Besides, in smallholder systems, approximately two-thirds of the rural population depends primarily on agriculture to survive and over 40% of household calories are provided by staple cereals (Jain et al., 2023).

This is why finding ways to sustainably increase smallholder agriculture production and productivity is imperative. This imperative is in fact encapsulated in the Sustainable Development Goal (SDG) 2.3 – which specifically intends to double the agricultural productivity and incomes of small-scale food producers by 2030 –, as well as in other more global SDGs such as SDG 1 “No Poverty” and SDG 2 “Zero Hunger” (United Nations, n.d.). For that matter, at the 2021 United Nations Food Systems Summit, a warning was put forth by the UN, underscoring that achieving the Sustainable Development Goal of eradicating global hunger by 2030 hinges on the prioritization of smallholder farmers (Bread for the world, 2023).

2.4.2. Yield gap

Smallholder farms are an interesting group to focus on, as they are relatively low yielding and have significant systematic productivity gaps (measured as the difference between actual and potential yield) (Jain et al., 2023).

Crop yields vary greatly between high-income and low-income countries, the latter reporting yields up to half those of high-income countries for cereals such as wheat and rice (FAO, 2014). In fact, while the Green Revolution brought about substantial increases in yield and production for essential crops in most parts of the world, the Global South has experienced a different trend with yield growth slowing, stagnating or even reversing in some regions (Ray et al., 2012).

In addition to their low yields, small farmers also have a large yield gap that can potentially be closed. Cui et al. (2018), in a study that tested the applicability of a decision-support integrated soil–crop system management (ISSM) program for growing crops in China, have found that a majority (61%) of smallholders achieved yields were at least 10% (up to 50%) below what could be obtained with the help of the ISSM. In another study, the authors reported that smallholders in Pakistan were realising only 32% of their potential crop yield (Abid et al., 2016).

This suggests that there is considerable potential to increase production and productivity in these smallholder systems by adopting improved technologies and practices (FAO, 2014; Mueller et al., 2012).

2.4.3. Vulnerability to climate change

South Asia's smallholder farms are projected to be among the most negatively affected by climate change[3] (Grain, 2021; Lobell et al., 2008; Ortiz-Bobea et al., 2021). They are particularly vulnerable to climatic extremes because of factors such as poor access to formal safety nets, persistent food insecurity, and heavy dependence on climate-sensitive agriculture, combined with restricted resources and capability to address and adjust to the impacts of climate change (Harvey et al., 2014). Yet, South Asia is strongly prone to such extreme weather events, including cyclones, floods, heat/cold waves, storms and droughts, and whose number is predicted to multiply (The World Bank Group, 2021).

Severe increases in temperature are also being forecast for this region. The IPPC has projected that the temperature may rise by 0.5–1.2 °C by 2020, 0.88–3.16 °C by 2050, and 1.56–5.44 °C by 2080 (depending on the scenarios of future development) (IPCC, 2007). This could lead to a 12% increase in the extend of heat-stressed zones in 2030 and 21% in 2050 (Tesfaye et al., 2017), making wheat production nearly unfeasible by 2050 in almost half of the Indo-Gangetic Plains, the major food basket in South Asia (Ortiz et al., 2008). Those changes in temperature and the unpredictability of weather events resulting from it are more likely to affect the viability of harvests and the length of cropping seasons, to increase the incidence of fluctuation in yields and market prices, and hence to aggravate the state of poverty and food insecurity in the region (Aryal et al., 2019).

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[3] See Appendix 4.

Weather and natural disasters directly linked to climate change have already generated billions in economic losses. In 2022, Asia and Pacific suffered $80 billion in economic losses due to extreme weather events, out of a total of 313 billion losses worldwide (Aon, 2023). In India, according to its Parliamentary Standing Committee on Agriculture, climatic events cause losses of 4 to 9% in the agricultural economy each year, which is an overall GDP loss of 1.5% (Venkatesh et al., 2018). Bangladesh, Afghanistan and Pakistan are not spared either, facing the same climatic disasters, causing major agricultural and economic losses (Grain, 2021). Overall, the World Bank Group (2021) has projected that by 2100, losses from climate change in GDP per capita for South Asian countries will be 18% in Bhutan, 13% in Nepal, 10% in India and 10% in Pakistan, which is about 7% higher than the global average.

Therefore, we focus on smallholder farmers in South Asia as they are key players in the economies of these regions, are essential to improving food security, overcoming poverty, maintaining ecosystems and protecting rural livelihoods, and as they have a large production gap to close and are among the most vulnerable to climate change.

The question now is what solution can be provided to these many challenges? How can the rising demand for food be met while mitigating environmental damage and reducing the vulnerability of this population to the effects of climate change? Put another way, could there be a solution that meets the intensification-mitigation-adaptation equation?

3. Turning farming ‘outside in’: vertical farming systems

One promising and innovative solution could lie in the adoption of VFS. Vertical farming, which is the practice of growing crops in vertically stacked layers with soilless cultivation systems and often within controlled environments (Despommier, 2009), has already shown impressive results on other continents, and has advantages that could overcome the challenges that modern agriculture is facing (Kabir et al., 2023; Mohapatra et al., 2023; Yeşil & Tatar, 2020). Using advanced technologies such as hydroponics, aeroponics, and aquaponics, this innovative method optimizes crop yield and resource utilization in confined spaces (Mohapatra et al., 2023).

But before delving into further details about the benefits of such systems and the reasons that make them a relevant solution, let's first precisely define what vertical farming is and explore the evolution of this innovation from its inception to its current utilization.

3.1. Definition of vertical farming

In principle, the definition of VF is simple: farming up rather than out (Al-Kodmany, 2018). However, the terminology remains ambiguous due to the lack of a standardised definition. The concept has been given many different descriptions depending on the author, the industry and the scientific paper (Kabir et al., 2023). The existence of multiple forms of VFS further complicates the grasp of the term (Van Delden et al., 2021).

In its simplest form, VF is the growing of crops indoors and with multiple stacked layers (Despommier, 2009). It can range from small portable installations to more complex high-rise structures (Butturini & Marcelis, 2020). VF is a form of controlled environment agriculture (CEA). It involves regulating certain aspects of the environment such as temperature, light, humidity, fertilisation, carbon dioxide concentration, irrigation, etc., in order to create a highly controlled environment for the plants (Kabir et al., 2023). This environmental control can be fully automated by leveraging modern technologies such as sensors, robotics, imaging technology and artificial intelligence (SharathKumar et al., 2020; Zhu & Marcelis, 2023).

Beacham et al. (2019) propose to divide VFS into two categories: those where crops are grown on inclined or fully vertical surfaces, and those that include several tiers of traditional horizontal growing platforms[4]. The first category, which is essentially green walls typically located on

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[4] See Appendix 5.

building facades, is not widely studied in the literature and will not be the focus of this thesis. What will interest us is the second category of VFS: the stacking of horizontal growing platforms on top of each other to form a vertical farm.

This form of VF can be accomplished in either fully confined controlled environment facilities, often known as 'Plant factories', or in glasshouses (Beacham et al., 2019). A vertical farm in a glasshouse should not, however, be confused with a greenhouse itself. The distinction between the two lies in the height. A vertical farm can be pictured as a stack of greenhouses placed on top of each other (Despommier, 2018). The advantage of such a glasshouse-based VFS is the use of natural light, with plants only needing to be supplemented with artificial lighting in periods of low light or for areas of the system that are far from the greenhouse walls (Beacham et al., 2019). Let us already specify that another way of resolving this distance problem – other than by using additional artificial light –, is to use a rotating mechanism that moves each tier gradually upwards to the top, thereby ensuring an equal level of light for each layer and thus maintaining uniform growing conditions for all the crops. This is, for example, the system used by the Singapore-based company Sky Greens (Benke & Tomkins, 2017).

A vertical farm can therefore rely on either natural or artificial light, or a combination of the two (Takeshima & Joshi, 2019). It can be set up in a variety of structures such as shipping containers, reconverted abandoned buildings, cellars and repurposed high-rise buildings (Van Delden et al., 2021). Lastly, a vertical farm can be located in an urban, suburban or rural area (Trimbo, 2019). However, the concept of vertical farms should not be confused with that of urban farms, which "*typically represent small outdoor farms or gardens to grow vegetables that are located in urban areas.*" (Stein, 2021, p. 1).

It should be noted that VFS are also sometimes referred to as sky farming, indoor farming, Vfarms and Zfarms (zero-acreage farms) (Stein, 2021; Thomaier et al., 2015).

3.1.1. Crop-cultivation systems

VFS count several innovative cultivation methods aimed at optimizing space use and resource efficiency (Mohapatra et al., 2023). The three main techniques for growing plants are: hydroponics, aeroponics and aquaponics. These are typically soil-free techniques, using nutrient-rich water solutions to supply vital nutrients directly to the roots of the plants (Al-Kodmany, 2018).

Hydroponic systems use water as the growing medium. The plant roots are kept in open troughs in which nutrient-enriched water is continuously circulating over them (Despommier, 2009). The water is collected in a central reservoir for recycling and subsequent reuse, enabling the system to operate in a closed loop (Kabir et al., 2023). Most vertical farms use this hydroponic method (Stein, 2021), which can be further divided into 2 sub-methods: nutrient film technique (NFT) and deep water culture (DWC) (Takeshima & Joshi, 2019). In NFT, a thin film of water continuously flows through a pipe, ensuring the roots receive a constant supply of nutrients. This pipe is situated in a growing tray, that always maintains contact with the roots, and that is angled to allow the water to flow back to the reservoir (Trimbo, 2019). In DWC, plant roots are completely submerged in an oxygenated nutrient solution (Van Delden et al., 2021).

Overall, these hydroponics systems are good for growing vegetables (tomatoes, spinach) and berries (Despommier, 2009). Schematic diagrams illustrating each technique are shown in Figure 1.

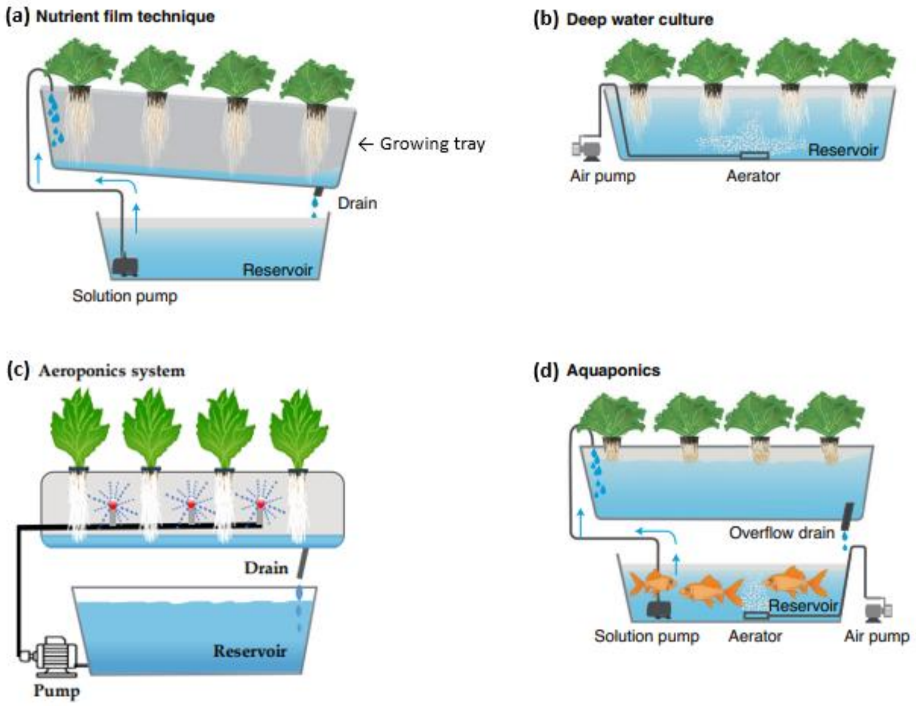

Figure 1 | Schematic diagrams of growing systems used in vertical farms: (a) nutrient-film technique (NFT); (b) deep water culture (DWC); (c) aeroponics; (d) aquaponics.

Source: Van Delden et al., 2021

In aeroponics systems, plants are suspended with their roots hanging in the air, and they are misted with nutrient-infused air or water vapor. Unlike hydroponic systems, which use water as the growing medium, aeroponics does not require a growing medium, and therefore doesn't require trays or containers to hold water (Al-Kodmany, 2018; Kabir et al., 2023). As the system operates in a closed loop and only uses mist, it allows for significant water savings – up to 95% less compared to traditional farming methods. This makes it particularly suitable for water-scarce regions. Another advantage of the aeroponic method is that it eliminates the need for fertilizers and pesticides while requiring minimal space (Al-Kodmany, 2018). Aeroponics systems are ideal for growing root crops (potatoes, carrots) (Despommier, 2009).

The combination of a hydroponic system with aquaculture results in what is known as aquaponics (Pantanella et al., 2012). "*Aquaponics [is a bio-system that] integrates fish farming with plant cultivation, creating a symbiotic relationship where fish waste provides nutrients for the plants, and the plants filter and purify the water for the fish.*" (Mohapatra et al., 2023, p. 275). These aquaponic systems offer many benefits: they supply two products (fish and fresh vegetables) from a single production unit, they are highly water-efficient (up to 90% less water compared to traditional soil-based agriculture) (Love et al., 2014) and their closed-loop design significantly reduces the necessity for fertilizers (Mohapatra et al., 2023). Finally, they are good for growing a variety of crops, from herbs and leafy greens to tomatoes and peppers (Mohapatra et al., 2023). While this technique is presently less widespread than hydroponics and aeroponics, it is starting to attract considerable interest (Al-Kodmany, 2018).

Other techniques exist, such as wick system, flood and drain method, and drip irrigation (especially good for grains like corn and wheat), but they remain marginal (Despommier, 2009; Stein, 2021).

All these techniques have in common that they enable vertical farms to grow a wide variety of crops while conserving water and lessening their environmental footprint (Mohapatra et al., 2023). Today, it is feasible to cultivate herbs, leafy greens, small fruits such as strawberries, tomatoes, cucumbers, fish, shrimp, and molluscs (Despommier, 2009).

3.2. A brief history

The roots of the concept of VF can be traced back as far as 600 B.C. with the Hanging Gardens of Babylon and their multilayered terraces (Al-Kodmany, 2018). But it wasn't until the 20th century that the modern era of VF began to take shape (Mohapatra et al., 2023). An American geologist, Gilbert Bailey, first introduced the term "vertical farming" in 1915. However, his concept differed significantly from today's understanding, as he proposed to farm "down" rather than "up", using explosives to dig up the soil (Crumpacker, 2018b). Later, during the 1930s, William Gericke pioneered hydroponic cultivation through his book "The Complete Guide to Soilless Gardening", establishing a crucial milestone in the evolution of VF (Van Gerrewey et al., 2021). Another breakthrough in the history of VF occurred in the 1980s when Åke Olsson, a Swedish environmentalist farmer, developed a spiral-shaped rail system to grow crops vertically, thereby proposing VF as a means of urban production (Al-Kodmany, 2018).

The concept of VF in its current sense was introduced in 1999 by Dickson Despommier, a microbiologist and professor at Columbia University (Yeşil & Tatar, 2020). With the help of his students, he developed the idea of a multi-story building where crops could be cultivated on multiple levels (Crumpacker, 2018b). The concept gained momentum through his visionary ideas, advocating vertical farms as a solution to enhance food safety for a rapidly growing urban population (Van Gerrewey et al., 2021). In addition, his book "The Vertical Farm: Feeding the World in the 21st Century" set the standard for contemporary discussions on the subject (Mohapatra et al., 2023).

Another key figure in popularizing the concept was the Japanese scientist Toyoki Kozai. During the same period, he developed a closed-loop, multi-layered production system with artificial lighting (Van Delden et al., 2021; Van Gerrewey et al., 2021).

Alongside Japan, other structures resembling modern VFS emerged in the Netherlands and the United States in the early 2000s (Van Delden et al., 2021). In 2009, the first profitable commercial vertical farm, Sky Greens, is built in Singapore. It consisted of over 100 towers, each 9 meters tall, that grew green vegetables (Crumpacker, 2018b). But for most other projects, more experimental, technicians struggled with technical issues and significant operational costs. By the mid-2000s, however, advancements in LED lighting technologies, automation, and hydroponic techniques fuelled a global expansion of VFS by making them more cost-effective. The VF industry then experienced steady growth, with many investors, startups, and established companies entering the market (Mohapatra et al., 2023).

3.3. Current state

Currently, commercial companies adopting VFS are to be found all over the world – in America, China, Japan, Singapore, Italy, France, Germany, the Netherlands, Norway, Sweden, England, South Korea, Saudi Arabia, the United Arab Emirates and Canada[5] (Kabir et al., 2023; Yeşil &

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[5] A table listing the leading vertical farms in production can be found in Appendix 6.

Tatar, 2020). New vertical farms are being planned in Russia, Hong Kong and Mongolia (Benke & Tomkins, 2017). An estimate by Markets&Markets (2023) suggests that the global VF market value is expected to grow at a rate of 24.7% from 2023 to 2028, thereby reaching 15.3 billion USD by 2028. The biggest surge is projected to occur in Asia Pacific, notably because of factors such as the decreasing availability of arable land for agriculture and the rapid population growth.

The regions actively embracing VF are East and Southeast Asia, as well as North America, most noticeably in countries such as Canada, Taiwan, Japan, Singapore, Malaysia and South Korea (Shamshiri et al., 2018). Especially, China, Japan and Israel are dedicating significant resources to research and development of VFS. This is because of the challenges they face concerning climate, pollution and urbanization (Benke & Tomkins, 2017).

In this way, we can see that VF has already been adopted by some countries as a response to the numerous challenges faced by traditional agriculture. The following section will therefore precisely detail the advantages found in VFS along with the opportunities they bring.

3.4. Rationale for vertical farming: advantages and opportunities of VFS

Vertical farming holds immense potential for growing high-quality crops year-round within controlled environments, while efficiently utilizing resources (Kabir et al., 2023). Higher yields, minimized or eliminated reliance on pesticides, herbicides and fertilizers, improved food quality and reduction of health risks, creation of jobs, continuous year-round production, water and land efficiency, food security and improved resilience to the impacts of climate change are some of the most cited benefits in the literature (Benke & Tomkins, 2017; Despommier, 2011; Zhu & Marcelis, 2023). These benefits can be examined through the prism of the three pillars of sustainability and thus categorized into economic, social and environmental dimensions.

3.4.1. Environmental benefits

"*Vertical farming offers unique opportunities to enhance environmental sustainability in agriculture*." (Kabir et al., 2023, p. 35). It has a lower environmental impact in terms of use of water, pesticides, herbicides, fertilizers and land, and it helps to restore the ecosystems.

Water recycling and reduced consumption

Advantage: A commonly highlighted advantage of VF is its lower water consumption. Many vertical farms quote a 70-95% water saving potential (Despommier, 2010; Stein, 2021) compared to traditional open-field systems. This water saving capacity mainly comes from the ability of VFS (aeroponics, hydroponics and aquaponics) to recirculate the nutrient water solutions multiple times (Gruda, 2019). The potential for decreased water consumption is also supported by water recovery, where water lost through transpiration and evaporation is collected and reused (Despommier, 2010).

Opportunity: This represents a significant opportunity, considering that agriculture consumes over 70% of the world's fresh water (Jain et al., 2023) and that water demand for this sector is forecast to increase by 60% by 2050, whereas overall water availability is projected to decrease as a result of climate change (Boretti & Rosa, 2019). This is especially concerning for Asia given that about 73% of the people affected by water scarcity currently live there (Boretti & Rosa, 2019). Therefore, VFS could be used for these water-scarce regions.

No or reduced pesticides, herbicides and fertilizers

Advantage: Another benefit of VF is that it virtually eliminates all requirements for fertilizers, herbicides, or pesticides (Benke & Tomkins, 2017). The use of closed-loop systems and precise monitoring considerably optimizes nutrient consumption, thereby reducing the need for pesticides, herbicides and fertilizers (Mohapatra et al., 2023). This enables VF to provide healthy organic food uncontaminated by chemicals (Benke & Tomkins, 2017) and to avoid soil and water contamination (Aktar et al., 2009; Hildebrandt et al., 2008).

Opportunity: The lack of knowledge and convenient access to agrochemicals tends to cause smallholders to overuse pesticides and fertilizer, in order to secure high yields (FAO, 2020). "*Going forward, such intensive management will damage soil productivity and trigger vicious cycles of environmental damage.*" (Guo et al., 2022, p. 512). Additionally, the use of pesticides has increased debt among farmers in South Asia. The adoption of VFS could thus protect both the environment and smallholders in South Asia (Brin et al., 2016).

Minimized land usage

Advantage: A key argument in favour of VF is its ability to decrease land usage. The practice of growing crops in vertically stacked layers enhances yield per square meter, reducing the need for extra land (Van Gerrewey et al., 2021). The use of soilless cultivation techniques further supports this reduction in land use (Benke & Tomkins, 2017). It is estimated that, depending on the crop type, one hectare of VF can potentially match the output of ten to twenty hectare of conventional soil-based farming (Despommier, 2015). "*Indoor [vertical] farming thus decreases pressure to convert idle arable land to agricultural use*." (Stein, 2021, p. 5).

Opportunity: The reduced land footprint of VF provides a relevant solution to address the issue of arable land availability. Indeed, throughout history, the increase in agricultural production has typically been achieved by expanding cultivated areas (FAO, 2014) and it is estimated that more than 1 billion hectares of new land (this is about the size of Brazil) will be needed to be converted to agricultural use in order to sustain the world's population by 2050, if current agricultural practices are maintained as they are today (Despommier, 2010; European Commission, 2019). However, a significant portion of the theoretically available additional land is either unsuitable for agriculture or can only be cultivated at significant ecological, social, and economic cost (Alexandratos & Bruinsma, 2012). Approximately half of the world's agricultural land is currently considered degraded and this is expected to worsen in the future, with significant areas of fertile soil being lost annually (Triodos Bank, 2019). "*This trend means that the planet is running short of farmland to feed a growing number of people*." (Benke & Tomkins, 2017, p. 13). This is where VF, by capitalizing on vertical space and decreasing dependence on arable land, can be seen as a viable solution.

Ecosystem restoration

Wood et al. explain this advantage by stating: "*The best reason to consider converting most food production to vertical farming is the promise of restoring [the] services and functions [of ecosystems].*" (cited in Al-Kodmany, 2018, p. 6). As highlighted earlier, VFS, with significantly reduced land requirements, not only help preserve remaining natural lands but also allow former agricultural lands to transform back to natural landscapes, thereby opening the potential for revitalizing soils and restoring ecosystems (Despommier, 2015; Van Delden et al., 2021). Furthermore, the minimized use of pesticides, herbicides and fertilizers in VF mitigates the risk of excessive nitrogen and phosphorus runoff into water sources (Germer et al., 2011).

However, it should be pointed out that the overall environmental performance of VFS depends largely on the inputs (energy source, growing medium, etc.) and the regional context, being mainly recommended for regions with extreme climates (Martin & Molin, 2019; Weidner et al., 2022).

3.4.2. Economic benefits

From an economic perspective, VFS offer several advantages compared to traditional agricultural systems: the controlled environment results in higher yields per square metre, year-round production and resilience to extreme weather events.

Higher yields

Advantage: An advantage that most authors mention is the high production yield of VF (Bunge et al., 2022). Despommier (2010) asserts that yields could increase by a factor of six or more, based on the crop type. This is because the environment and its various parameters (light, water, heat, humidity, amount of nutrients) are controlled and optimised to create the ideal conditions for the crops to grow. Under these conditions, crops grow faster and larger, significantly increasing annual yields compared to traditional farming methods (Despommier, 2009; Kalantari et al., 2018). The closed controlled environment also prevents crop losses caused by pests and diseases (Germer et al., 2011). Vertical farms with advanced LED lighting can further optimise plant growth by adjusting wavelengths, intensity and photo-period (Stein, 2021). A striking example is that of a 25.000 square metre Japanese farm producing 10.000 heads of lettuce a day – i.e.100 times more per square foot than traditional methods – while using 99% less water, 40% less energy and 80% less food waste than open fields (Kohlstedt, 2015).

Opportunity: As previously mentioned, the farming sector faces the immense challenge of feeding an ever-growing population whereas there is limited potential for expanding agricultural land. Consequently, the majority of the required increase in production must be achieved through higher yields and greater crop intensity (Alexandratos & Bruinsma, 2012). This is especially true for smallholders who are relatively low yielding and have a significant productivity gap (as previously discussed in section 2.4.2.). VF could help them narrow this gap and meet the challenge of producing more.

Year-round production

Advantage: "*Another advantage of VF is that, unlike traditional farming which can only be carried out at a particular time of the year, plants inside a VF can grow all the time throughout the year.*" (Kalantari et al., 2018, p. 44). The controlled environment of VFS removes the limitations imposed by seasonal variations, thereby enabling multiple harvests of short-period crops during an annual cycle (Beacham et al., 2019). The closed design of VF also allows for production anywhere, from harsh tundra to arid desert, without concerns for local climate and weather conditions (such as precipitation, soil, temperature) (Despommier, 2009; Kabir et al., 2023). A notable example of this versatility is Eurofresh Farms, located in the Arizona desert, which grows a large number of cucumbers, tomatoes and peppers all year round (Despommier, 2015).

Opportunity: Since climate variability explains nearly 60% of yield fluctuations, thereby profoundly affecting farmers' incomes and food production (Aryal et al., 2019), it is an advantage particularly attractive. This is especially advantageous for smallholders in South Asia, where 60% of cultivated land is rainfed, making precipitation variability a critical factor in determining their production and revenue (Bhatta & Aggarwal, 2016).

Resilient to extreme weather events

Advantage: VF shields crops from outside conditions, providing resilience to catastrophic climatic events such as flooding, fires, hailstorms, droughts, tornados, hurricanes and other devastating natural events (Despommier, 2015; Stein, 2021). This eliminates the risk of losing crops due to such events (Van Gerrewey et al., 2021).

Opportunity: As outlined in section 2.4.3., South Asia's smallholder farms are particularly vulnerable to climatic extremes, and in those countries, natural disasters directly linked to climate change have already generated billions in economic losses. Considering that this situation will worsen in the years to come, the relevance of an isolated production system from the external conditions can be better understood (Yeşil & Tatar, 2020).

More generally, VF can offer economic advantages such as a lower cost base due to protection from extreme weather events (Benke & Tomkins, 2017) and stability in prices and the supply chain thanks to its capacity to control the growing environment of the plants (Stein, 2021). Also, Bunge et al. (2022), in a systematic scoping review, found consensus that VF results in slightly higher revenues. Ultimately, VF creates new market opportunities and stimulates research and development in innovative agricultural technologies (Al-Kodmany, 2018; Kabir et al., 2023).

3.4.3. Social benefits

Creation of jobs

One advantage of the development of the VF market is that it will create new employment opportunities (Despommier, 2015). These include direct jobs, such as workers to manage plantation, cultivation, supervision, harvest and quality control of the crops, maintenance workers, engineers for the installation of systems, agronomists, IT specialists and project managers, but also indirect jobs such as biochemists, biotechnicians, engineers and scientists for research and development of VFS, besides marketing and retail staff (Benke & Tomkins, 2017; Kalantari et al., 2018).

Improved food quality and reduction of health risks

Advantage: Another benefit of cultivating crops with VFS is that, unlike open-field farming, the controlled environment can significantly help reduce or even eliminate the risk of diverse damaging pests carrying diseases (Yeşil & Tatar, 2020). Moreover, the minimal to zero pesticides and herbicides requirements of VFS further reduce health risks for humans and provide better food quality (Voss, 2013).

Improved food security

Advantage: Overall, VFS allows fresh, nutritious and pesticide-free products to be grown and available all year round, thereby ensuring a dependable, steady and localised supply of food. In this way, VF contributes to improving food security (Germer et al., 2011; Mohapatra et al., 2023). This is the case, for example, of the Singaporean company Sky Greens which brings greater food security to the city (Benke & Tomkins, 2017).

Opportunity: As seen in section 2.4.1., smallholders will have an important role to play in improving food security and supporting the growing demand for food. The adoption of VFS can help them meet these challenges.

In conclusion, we see that if all these reported benefits can be met in practice, vertical farming would present itself as a relevant solution for smallholders in South Asia to cope with the current and future challenges of agriculture. However, the literature highlights certain drawbacks of VF that could preclude its viable application everywhere while also ensuring environmental compatibility and social acceptability. The following section will elaborate on these barriers.

3.5. Barriers for the use of vertical farms in smallholders in South Asia

Major barriers exist regarding the range of crops produced, consumer acceptance, the search for qualified employees, energy efficiency and economic profitability, that hinder a larger adoption of VFS (Benke & Tomkins, 2017; Van Delden et al., 2021).

Limited crops diversity

One major limitation of VFS is that it cannot grow every type of crop (Al-Kodmany, 2018). Vertical farms currently prioritize high-value crops, such as leafy greens, microgreens, berries, tomatoes, herbs, cucumbers, radishes and ornamentals[6], that have short height and are economically profitable because of their short growth cycles (Kalantari et al., 2017; Van Delden et al., 2021). Producing staple foods like cereal crops is presently economically unviable in nearly all markets (Al-Kodmany, 2018; Triodos Bank, 2019). This is problematic considering that cereal grains are the most important staple food for humans (Germer et al., 2011) and that smallholders produce about 30% of all cereals in Asia (Gomez Y Paloma et al., 2020). This limitation in production range could therefore affect the adaptability of VFS (Kabir et al., 2023) and its potential to address global food security (Kuljanic, 2022).

However, authors like Kabir et al. (2023) argue that VF has diversification potential, enabling the cultivation of a wide array of crops, on condition that more advanced technologies are integrated. It should also be mentioned that other food items (like shrimp, mussels and crayfish) have already been successfully commercialized by vertical farms (Despommier, 2015) and that recently, the German company Infarm has succeeded in producing wheat with an impressive yield of 11.7 kg per m^2, "*making a significant milestone in the journey towards growing staple crops for global food security through vertical farming*." (Zhu & Marcelis, 2023, p. 13).

High initial investment and operational costs

Another barrier to widespread adoption of VFS are the high upfront investment costs as well as the operational costs (Kabir et al., 2023). Setting up a vertical farm, especially a highly technological one and from scratch, requires substantial capital investments in construction, land, infrastructure, automated systems, and technology (Mohapatra et al., 2023). For example, in comparison to a high-tech greenhouse, a vertical farm can have up to ten times higher

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[6] See Appendix 7.

investment costs per square meter of growing space (Butturini & Marcelis, 2020, as cited in Van Gerrewey et al., 2021). For a more concrete illustration, estimates by Heat, Zhu, and Shao (2012) suggest that the initial costs for a 60ha vertical farm could easily be over $100 million (Takeshima & Joshi, 2019). This can pose a significant hurdle for startups and smallholder farms in particular (Mohapatra et al., 2023; Stein, 2021).

VF also requires significant operational costs for energy, nutrient delivery systems, nutrient solutions, water, growth equipment and staff costs (Banerjee & Adenaeuer, 2014), which further increases the costs. For example, the estimated total operating costs per m^2 for a vertical farm can be up to five times more than for a high-tech greenhouse (Butturini & Marcelis, 2020, as cited in Van Gerrewey et al., 2021). This compromises the profitability of VF, as demonstrated by the 2019 Global CEA Census report (Autogrow and Agritecture Consulting, 2019), which surveyed 316 participants from 54 countries, revealing a profitability of 38% for vertical farms compared to 45% for greenhouses.

It is however worth noting that there is limited published research on the economic analysis of VFS. Further research is needed to obtain reliable and generalizable results (Van Delden et al., 2021; Yeşil & Tatar, 2020). Moreover, utilizing pre-existing infrastructure rather than constructing a new facility should reduce the investment costs of VF (Brin et al., 2016). Furthermore, technological advancements in lighting and automation, coupled with the benefits of VF such as resource efficiency, year-round production, and climate resilience, should make it more economically viable in the long run (Kabir et al., 2023; Mohapatra et al., 2023).

Energy use and associated GHG emissions

The main argument against VF is that indoor cultivation (whether in a glasshouse or an enclosed controlled environment facility) consumes more energy compared to traditional open-field farming (Beacham et al., 2019; Bunge et al., 2022; Graamans et al., 2018). VF indeed requires energy both for technical installations and for maintaining crops growth conditions (light, heating/cooling, running water, air quality, etc.), with a significant portion used to supplement crops with artificial light (Germer et al., 2011; Zhu & Marcelis, 2023). According to research conducted by Kozai, Niu, & Takagaki (2020), artificial light constitutes 70-80% of the total electricity consumption. However, with the advent and adoption of light-emitting diode (LED) technology, this consumption has been reduced by 30 to 40% compared to traditional fluorescent lamps (Kozai, 2018).

Nevertheless, LED lighting systems continue to account for the largest share of electricity needs (followed by the demands for irrigation, heating, and ventilation)(Martin & Molin, 2019), which greatly impacts GHG emissions, resulting in higher levels than those of traditional agriculture (Bunge et al., 2022). A study by Al-Chalabi (2015) explored the feasibility of a hypothetical multi-floor tower for lettuce production using artificial lighting, water circulation and solar panels on the roof. The study found that the solar panels could generate enough power to light and pump water. However, from a life cycle perspective, the results indicated a carbon footprint (CO2/kg of lettuce) five times higher in the summer and two times higher in the winter compared to conventional field-grown lettuce (when using conventional energy sources).

But the environmental impact of a vertical farm in terms of energy depends on how electricity is generated (Van Delden et al., 2021). "*Whether they are fossil fuel- or renewable-powered makes a significant difference.*" (Kuljanic, 2022, p. 2). Using nuclear or renewable energy sources in VFS, such as solar, hydro and wind power, could decrease the carbon footprint of these systems and enhance their sustainability (Al-Chalabi, 2015; Martin & Molin, 2019; Mohapatra et al., 2023).

In brief, VF is feasible in regions with abundant sunlight (Al-Chalabi, 2015) and holds significant potential in areas where energy production is sustainable (Van Delden et al., 2021). On this matter, it is worth mentioning that India ranks as the world's fifth-largest solar photovoltaic (PV) market, with nearly 50 GW of total installed capacity (The World Bank Group, 2021). Furthermore, India, along with Sri Lanka, possesses some of the world's highest potentials for offshore wind energy, while Bangladesh is seriously considering the use of floating solar PV panels in land-scarce areas (The World Bank Group, 2021).

Social resistance

Research has highlighted another drawback of VF: social resistance (Al-Kodmany, 2018; Specht et al., 2015). In general, acceptance of VFS is negative as consumers perceive these methods of food production as unnatural (Al-Chalabi, 2015; Mina et al., 2023). Additionally, consumers often have a poor understanding of soilless cultivation, which exacerbates this negative perception (Van Gerrewey et al., 2021), and the term "plant factories," sometimes used to describe VF, can make some people think of the products as "Frankenstein food" (Curtis, 2016; Van Delden et al., 2021).

Nonetheless, the perception and acceptance of VFS vary significantly across regions and cultures. Asia, particularly Japan and South Korea, shows greater acceptance, whereas Europe and the United States are more reluctant (Van Delden et al., 2021).

Qualified workers

The shortage of qualified personnel is another challenge that VF may encounter (Despommier, 2018). Indeed, the complex management and maintenance of VFS and associated technologies require workers with a high level of expertise across various fields, from agriculture and engineering to architecture and data sciences (Kabir et al., 2023; Kuljanic, 2022). Yet, there is currently a shortage of such trained personnel and advanced training programs in CEA (Despommier, 2018; Kabir et al., 2023), especially in South Asia (Brin et al., 2016). As the VF industry is still new, it struggles to share knowledge, develop best practices, and set standards, despite ongoing progress (Stein, 2021).

Urban specific

We have seen that VFS were initially designed to address urban issues, and that the literature predominantly discusses them in relation to urban areas. Authors such as Brin et al. (2016) believe that, at the start, the most promising environment for VF is the urban setting. Van Gerrewey et al. (2021) echo this view, adding that vertical farms are viable only in certain niche markets and particular geographic locations depending on the extent of urbanization, given their substantial investment and operational expenses. VF is thus primarily considered an urban solution.

However, VFS must depend on and be tailored to the specific socio-economic context of their location (Van Delden et al., 2021), and there are no real contradictions in their use in rural areas (Beacham et al., 2019). For that matter, a study conducted by Agrilyst (2017) based on a survey of 150 indoor farms across eight countries, has shown that indoor farming is also a rural phenomenon, with 47% of respondents operating in rural zones (as cited in Cosgrove, 2018). VF in rural areas can actually take advantage of land that is unsuitable for conventional agriculture, such as poor-quality soils, depleted or heavy metal-contaminated soils, or former industrial sites that would otherwise remain unused (Beacham et al., 2019).

3.6. Conditions for successful development of VF

From the previous section, we have thus seen that from technical limitations to economic and social concerns, VF has a number of barriers to overcome if it is to be successfully adopted. Here are several conditions for its viable application everywhere:

- Technological optimization is necessary to lower costs and achieve cost parity with traditional farming methods (Mohapatra et al., 2023; Van Delden et al., 2021).
- R&D efforts should focus on lowering the high energy consumption of VFS and these must use renewable energy sources (Kuljanic, 2022; Zhu & Marcelis, 2023).
- Education and communication regarding VF should be improved to enhance social acceptance (Aryal et al., 2019; Van Gerrewey et al., 2021).
- The VF industry must provide accessible and expanded education to facilitate the development and training of highly skilled farmers and managers (Crumpacker, 2018a).
- Efficient support from institutions and extensive financial aid from governments are essential to making VF feasible for smallholders (Aryal et al., 2019; Benke & Tomkins, 2017; Kuljanic, 2022).

PART 2 – EMPIRICAL STUDY

4. Research methodology

4.1. Purpose of the empirical study

From the literature review, we have learned that vertical farming holds great promise for addressing the current challenges faced by traditional agriculture. It offers numerous advantages such as high yields, continuous year-round production, minimized or eliminated reliance on pesticides or herbicides, water efficiency, and improved resilience to the impacts of climate change. However, despite its confirmed potential, certain limitations hinder its widespread practical implementation. VF necessitates substantial investments and capital, adequate resource availability such as energy, skilled labour, and R&D efforts in technological optimization, among others, to make it feasible. A methodology is therefore needed to assess the degree of feasibility of VF in a given area.

For this study, we have chosen to analyse the South Asia region for the reasons given in section 2.4 and because the countries in this part of the world have few, if any, vertical farms. We therefore believe that it is worthwhile to investigate whether VF could be a feasible and sustainable solution for smallholder farmers in South Asia. Furthermore, to our knowledge, no other studies have assessed the feasibility of VF there. Hence, our study aims to fill this gap.

As a reminder, the objective of this thesis is to answer the following research question:

Is vertical farming a relevant and feasible solution for sustainable agriculture among smallholders in South Asia?

4.2. Methodology

To answer our research question, a quantitative approach will be employed. We have decided to replicate the methodology used by Paucek et al. (2023) in their research paper entitled "*A methodological tool for sustainability and feasibility assessment of indoor vertical farming with artificial lighting in Africa.".* The research method that will be used to assess the feasibility and sustainability of implementing VFS in South Asian countries is the Synthetic Measure of Development (SMD). The SMD is a composite index designed to evaluate and quantify the level of development in different regions or countries. It is created by combining multiple individual indicators, which reflect various dimensions of development (environmental, economic, social, technological, etc.), into a single index (OECD et al., 2008). Composite indexes are valuable for evaluating complex phenomena that cannot be adequately represented by one indicator alone. They also allow for the comparability of variables (Kiselakova et al., 2020). Finally, they prove useful in setting policy priorities and benchmarking country performance (OECD et al., 2008).

A synthetic measure will thus be constructed to evaluate VF feasibility and sustainability in 7 South Asian countries. These countries are Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan, and Sri Lanka. The research framework of this study considers the most technologically advanced VFS, i.e. in a controlled enclosed environment with artificial light. However, if the results of the study suggest that implementing a vertical farm is not feasible in a particular country, this does not imply that a simplified VFS using locally available materials cannot be implemented and be a relevant solution (Paucek et al., 2023).

4.2.1. General methodology and data collection

To assess the feasibility of VF in the 7 countries studied, 148 specific Development Indicators were selected. We assumed that Paucek et al.'s choice of indicators was relevant, and therefore we adopted the same set, except for the indicators *Domestic credit provided by financial sector (% of GDP)*, *Technicians in R&D (per million people)*, and *Use of insecticide-treated bed nets (% of under-5 population)* which were removed for lack of data. Besides these, the following 4 indicators were added: *Claims on private sector (annual growth as % of broad money), Per capita food production variability (constant 2014-2016 thousand int$ per capita)*, *Per capita food supply variability (kcal/cap/day)* and *Electricity production from oil sources (% of total).* The complete list of selected indicators is provided in Appendix 8. The data were retrieved from World Bank and FAO databases.

From the 148 indicators chosen for this study, 14 macro-categories[7] adapted to the main requirements of VF were developed, which were then further organised into 3 macro-areas[8]. The 3 macro-areas are:

(1) **Urban Agriculture Productivity and Food Security** (comprising the macro-categories Urban Development, Agriculture Development, Food Security and Climate Change Vulnerability)

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[7] A macro-category is a class of several specific Development Indicators of the same nature.

[8] A macro-area is a broader class that groups together several macro-categories. It represents the overarching themes that encapsulate the various dimensions of development relevant to vertical farming.

(2) **Economic and Political Implications** (comprising the macro-categories Economy and Growth, Private Sector, Financial Sector, Infrastructure, Trade, Aid Development Effectiveness and Science & Technology)

(3) **Resources Availability and Social Implication** (comprising the macro-categories Energy, Water and Environment and Social).

For each macro-category and macro-area, a synthetic feasibility index (SFI) was calculated[9]. This enabled an initial targeted and precise analysis of the phenomenon before conducting the evaluation of the final index. The final SFI per country was obtained[10] by averaging the SFIs of the 14 macro-categories.

Following this initial analysis of the feasibility of VFS in South Asia, a subsequent analysis was carried out to assess the sustainability of such systems. The sustainability analysis was conducted only for countries where the results indicated that VF is feasible. As a result, the sustainability assessment can be understood as a statistical measure that informs the viability of VFS in South Asian countries where it shows the greatest feasibility. The sustainability assessment took into account the three main pillars of sustainability, namely environmental, economic, and social, represented by the macro-categories *Water and Environment*, *Economy and Growth* and *Social*, to which four additional macro-categories were added due to their significance in achieving VF sustainability (*Urban development*, *Energy*, *Food Security* and *Science & Technology*). The complete list of macro-categories and indicators used for evaluating sustainability is provided in Appendix 21.

Using the same procedure as for the SFI, a synthetic sustainability index (SSI) was built for countries where FV was found to be the most feasible.

4.2.2. Construction of the synthetic index

The SMD construction procedure was carried out using a linear ordering method based on average and standard deviation. The construction process followed the following sequential stages for both the feasibility and sustainability assessment:

(1) Selection of all suitable indicators and retrieval of the selected indicators from the World Bank and FAO databases for compilation into observational matrices.

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[9] See Appendices 9 and 14.

[10] See Appendix 19.

(2) Classification of all the chosen indicators into the appropriate macro-category. The same indicator can be placed in several macro-categories, thereby increasing its influence on the final score.

(3) Determination of the nature of each variable according to the macro-category to which it belongs and to its relationship with the feasibility or sustainability objective. A variable can be classified as stimulant, destimulant, or nominant[11] (Bartniczak & Raszkowski, 2019).

We classified the indicators in the same manner as Paucek et al. All were classified solely as stimulant or destimulant, with no nominant variables in the set. The nature of all 148 variables can be found in Appendix 8.

(4) To ensure comparability, normalisation of all indicators using a zero-unitarization method (also known as Min-Max Normalisation) according to how the indicator was classified:

For stimulant variables:

$$n_i = \frac{x_i - x_{min}}{x_{max} - x_{min}}$$

For destimulant variables:

$$n_i = \frac{x_{max} - x_i}{x_{max} - x_{min}}$$

where x_i represents the value of the variable in the i-year and x_{max} and x_{min} denoting the maximum and minimum values among all 7 countries for the same i-year. As a result of unitarization, all indicators take values within an identical interval [0;1]. The closer it is to 1, the more it indicates favourable conditions.

Normalisation was performed on a matrix encompassing data from 2004 to 2023. To capture the most recent trends, the data from the last five available years were used. But if the most recent data were not available, data from earlier years were utilised. For some indicators, only one year of data was available[12].

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[11] *Stimulants are variables whose high values are desirable from the assumed point of view, e. g. the level of sustainable development, while the low ones are undesirable. Destimulants are variables whose low values are desirable from a particular point of view, while high values are undesirable. Nominants are variables for which there is an "optimal" level, and both downward and upward deviations are undesirable.* (Kiselakova et al., 2020, p. 62).

[12] See details in Appendix 8.

(5) Calculation of an average normalised value n_{av} for each country for each indicator, by averaging the values for each of the considered years.

(6) Calculation of a synthetic index x_j for each country for each macro-category by taking the arithmetic mean of all normalised values n_{av}. The same procedure was followed for the macro-areas.

Some indicators had no available data or partial data for certain countries[13]. When too many indicators forming a macro-category were missing, the synthetic indicator was not calculated.

(7) Construction of the final synthetic feasibility index (SFI) and synthetic sustainability index (SSI) for each of the 7 countries by taking the weighted average of the synthetic indexes determined for the 14 macro-categories for the SFI and for the 7 selected macro-categories for the SSI. As a reminder, a SSI is calculated only for countries where implementation of VFS is feasible.

This weighted average approach has its justification because certain aspects contained in some macro-categories have a larger impact on the feasibility of implementing VFS. This is particularly the case for aspects such as energy, financing, technology and education, as discussed in section 3.6. on the conditions for successful development of VF. The following weightings were applied: 6% for urban development, 7% for infrastructure, 7% for aid development effectiveness, 7% for social, 10% for financial sector, 14% for energy, 14% for science & technology, and 5% for the remaining macro-categories. In opting for this weighting scheme, we deviated from the methodology adopted by Paucek et al.

(8) Classification of the 7 South Asian countries into four groups according to the scheme:

Very favourable: $x_j \geq \bar{x} + S_x$
Favourable: $\bar{x} \leq x_j < \bar{x} + S_x$
Unfavourable: $\bar{x} - S_x \leq x_j < \bar{x}$
Very unfavourable: $x_j < \bar{x} - S_x$

where $\bar{x}$ is the synthetic index's arithmetic mean and S_x the standard deviation.

(9) Final step: Visual representation of countries classification on a map.

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[13] See the complete list of missing indicators in Appendix 24.

4.2.3. Hypothesis and limitations

As mentioned earlier, we made two assumptions for this part: first, that Paucek et al.'s selection of indicators to include in the macro-categories was valid, and secondly, that their classification as stimulant or destimulant was also accurate.

In terms of the limitations of the methodology used, the main ones lie in:

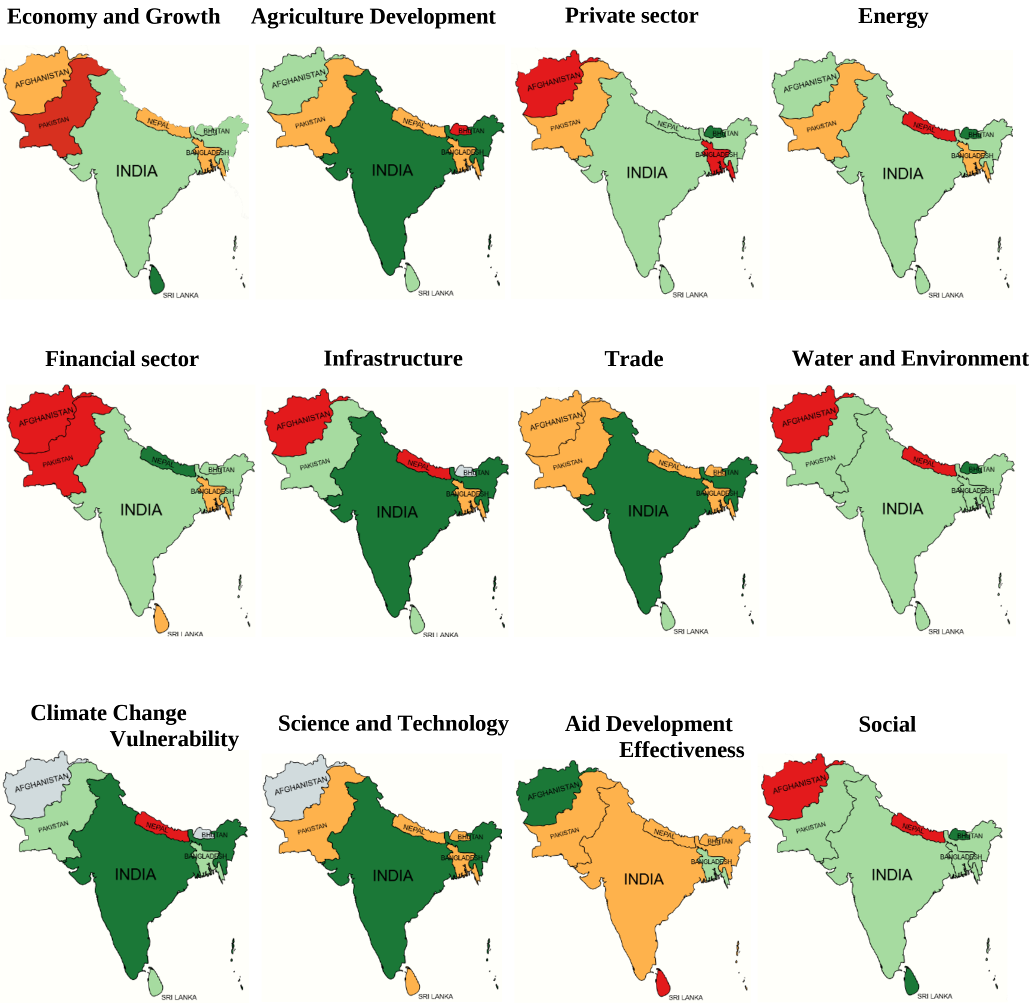
- Insufficient data available for certain countries and indicators selected.
- There is currently no established agreement on which indicators are most appropriate or pertinent for evaluating feasibility or sustainability of agriculture. Additionally, there are no established frameworks for implementing VF within a given country (Paucek et al., 2023).
- With normalised values, proportionality is not preserved, and they instead reflect the percentage within the range of maximum and minimum values. Indicators with outliers will exert a stronger influence on the composite indicator (OECD et al., 2008).
- The choice of country-level analysis does not capture potential differences that may exist within different regions of the same country (Paucek et al., 2023).

5. Results

5.1. At macro-category level[14]

First and foremost, it is important to note that five SFI for the macro-categories could not be calculated due to a lack of data: *Infrastructure*, *Climate Change Vulnerability*, and *Food Security* for Bhutan, and *Climate Change Vulnerability* and *Science & Technology* for Afghanistan.

Among all the macro-categories studied, India was categorised as "very favourable" in 6 out of 14 macro-categories (42.86%), followed by Bhutan (28.57%) and Sri Lanka (21.43%). In contrast, Pakistan was not classified as "very favourable" in any macro-category, while Bangladesh and Nepal were categorised as "very favourable" only once (7.14%). Figure 2 provides a visual representation of the categorisation of each country across the 14 macro-categories.


Economy and Growth

Agriculture Development

Private sector

Energy

Financial sector

Infrastructure

Trade

Water and Environment

Climate Change Vulnerability

Science and Technology

Aid Development Effectiveness

Social

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[14] See Appendix 9, 12 and 13 for the complete results tables.

Figure 2 | Categorization of the feasibility of vertical farming for each of the 14 macro-categories in South Asian countries.

*Note**:** Generated with MapChart (https://www.mapchart.net/).*

The macro-categories with the highest number of countries classified as "very favourable" were *Social* and *Urban Development*, at the yet low rate of 28.57%. Conversely, the macro-categories *Trade*, *Science & Technology*, and *Aid development effectiveness* accounted for the largest number of “very unfavourable” and “unfavourable” countries (with 71.43%), followed by the macro-categories *Economy and growth*, *Agriculture Development*, *Financial Sector* and *Urban Development*, with 57.14% of “very unfavourable” or “unfavourable”.

The country categorised most frequently as “very unfavourable”, in 6 out of the 14 macro-categories, was Afghanistan, followed by Nepal (5 out of 14). Afghanistan qualified as “very unfavourable” in *Private sector, Financial sector, Infrastructure, Water and Environment, Social* and *Food Security*. However, the country found to have the highest combined number of "unfavourable" and "very unfavourable" classifications was Nepal (78.57%). On the contrary, India was classified as "very favourable" or " favourable" 92.86% of the time. The only category in which it was classified as "unfavourable" was *Aid Development Effectiveness*. Bangladesh was the country more times categorised as “unfavourable” (57.14%) among all macro-categories.

Finally, the macro-categories that showed the greatest disparity between countries were *Science & Technology* and *Trade*, with coefficients of variation of respectively 196.671% and 81.446%[15]. In contrast, *Economy and Growth* was the most uniform macro-category among the countries, exhibiting a coefficient of variation of 13.516%.

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[15] See Appendix 10 for the detailed table of these parameters.

5.2. At macro-area level[16]

Urban Agriculture Productivity and Food Security

In this macro-area, India reported the highest SFI (0.68), notably due to high *Climate Change Vulnerability* and *Food security* scores. In second and third place were Bangladesh (0.537 SFI) and Pakistan (0.490 SFI). In terms of *Urban Development*, the best index was obtained by Bangladesh (0.644), closely followed by India (0.639). Sri Lanka displayed the highest score in the macro-category *Food Security* (0.803), while India and Bangladesh resulted as the most vulnerable to climate change[17]. Overall, the classification of countries indicated that the area most favourable for safe urban agricultural production was India ("very favourable" classification), while the least favourable country was Bhutan ("very unfavourable" classification) with a SFI of 0.269.

Economic and Political Implications

In this macro-area, India once again achieved the highest SFI of 0.662. This can be explained by its top scores in *Financial Sector*, *Infrastructure*, *Trade*, and *Science & Technology*. In fact, India was the only country to be classified as "very favourable", followed by Bhutan, which was classified as "favourable". All other countries were categorised as "unfavourable" in this macro-area. The lowest SFIs for this macro-area were attributed to Pakistan (0.262) and Afghanistan (0.288), notably due to getting the worst *Economy and Growth* and *Financial sector* results.

Resources availability and Social Implication

The results revealed a strong leading position of Bhutan in this macro-area, with a SFI of 0.80. Due to best scores in *Energy* (0.977) and *Water and Environment* (0.740) and second-best score in *Social* (0.683), this country ranked as very favourable for VF feasibility within this macro-area. Countries that were categorised as "favourable" were Sri Lanka (0.691), India (0.620) and Bangladesh (0.565). The country with the least resources and social requirements necessary to implement VF was Nepal, which was classified as "very unfavourable" with a SFI of 0.198.

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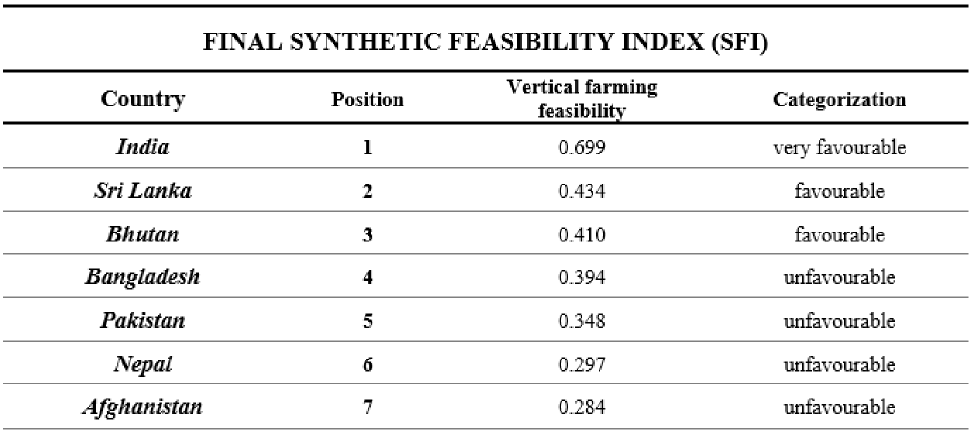
[16] See Appendix 14, 17 and 18 for the complete results tables.

[17] As a reminder, the *Climate Change Vulnerability* SFIs for Afghanistan and Bhutan could not be calculated due to a lack of data.

5.3. At country level[18]

Regarding the final SFI, India achieved the highest score with an index of 0.699. It is the sole country to achieve a "very favourable" categorization. Sri Lanka and Bhutan ranked as favourable for overall VF feasibility with indices of 0.434 and 0.410 respectively. All other countries were classified as "unfavourable”. The lowest SFI was recorded by Afghanistan (0.284). The overall ranking of the feasibility of vertical farming in South Asia is as follows:



FINAL SYNTHETIC FEASIBILITY INDEX (SFI)

Country	Position	Vertical farming feasibility	Categorization
India	**1**	0.699	very favourable
Sri Lanka	**2**	0.434	favourable
Bhutan	**3**	0.410	favourable
Bangladesh	**4**	0.394	unfavourable
Pakistan	**5**	0.348	unfavourable
Nepal	**6**	0.297	unfavourable
Afghanistan	**7**	0.284	unfavourable

Figure 3 | Categorization of vertical farming general feasibility in South Asian countries.

Since India demonstrated the greatest feasibility for VF in South Asia, a SSI was calculated solely for this country. India obtained a SSI of 0.671, with higher social sustainability outcomes and a lower synthetic value for the economic analysis of sustainability.

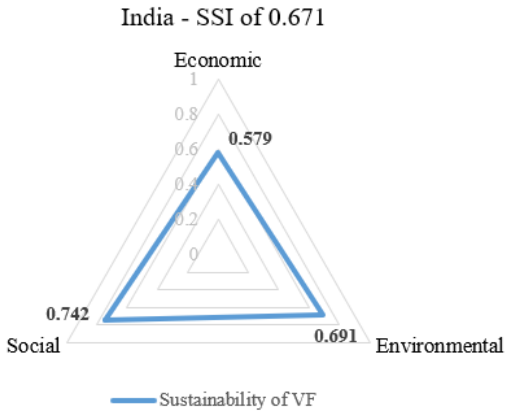


Figure 4 | Assessment of the economic, social and environmental sustainability of vertical farming for India.

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[18] See Appendices 19 and 20 for the complete results tables.

6. Discussion

The aim of this study was to assess the degree of feasibility and sustainability of VF for smallholders in South Asia. What we calculated was first a Synthetic Feasibility Index (for each of the 7 countries studied, based on 148 specific Development Indicators) and then a Synthetic Sustainability Index (for the countries where the results indicated that VF was the most feasible).

First and foremost, it is essential to specify that the method used provides a relative ranking of South Asian countries rather than an absolute one. A country classified as "very favourable" should be understood as demonstrating the highest feasibility potential among the studied group and not as demonstrating absolute proof of feasibility.

Our results show that the three countries demonstrating the best prospective for VF implementation are India, Sri Lanka and Bhutan[19]. In these nations, improving existing agricultural systems with VFS could be achievable. These results align with the conclusions of the report by Brin et al. (2016), in which the authors state that VF models are increasingly emerging as a solution in India and Sri Lanka.

However, these three countries do not possess the same strengths nor face the same barriers in the implementation of VFS. India appears to be the most favourable of the three for urban agricultural production due to higher *Urban development*, *Infrastructure* and *Agriculture development.* In 2023 in India, the level of urbanization (urban population as a percentage of the total population) was 36.36% (Statista, 2024) and it is estimated that it will almost double between 2018 and 2050 (United Nations, 2019). So, as the urban population will continue to rise, India will encounter significant challenges in feeding its city dwellers and consequently emerges as a favourable location for the development of vertical farms[20].

India also showed an excellent level of investment in the *Science and Technology* macro-category, significantly ahead of the other countries (“very favourable” categorization for India compared to “unfavourable” categorization for Bangladesh, Bhutan, Nepal, Pakistan and Sri Lanka). This places India as the most capable of fulfilling the technological and scientific conditions for the development of vertical agriculture. The other countries may face significant

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[19] The results for Bhutan must be analysed with caution as nearly 20% (29 out of 148) of the specific Development Indicators for this country lacked data.

[20] We would like to remind that VF is primarily an urban solution.

challenges in adopting VFS due to the scientific and technological requirements needed for setting up and maintaining a vertical farm.

Then, and as we have seen, energy requirements - and particularly access to electricity - is a crucial factor for the successful implementation of VFS. In this regard, this study shows that Bhutan stands as the best positioned country to adopt VFS, followed by Sri Lanka. On the other hand, operating vertical farms in Pakistan, Nepal and Afghanistan would be a riskier venture, as they experience the highest values lost due to electrical outages (as a % of sales for affected firms). Beside this, Bhutan is also the best-positioned country in South Asia for supplying the necessary water and social workforce required to implement vertical farms ("very favourable" categorization for VF feasibility within the macro-area *Resources availability and Social Implication*).

Regarding agricultural water requirements, the countries least equipped, and likely to face the greatest challenges in meeting this need, are Nepal and Afghanistan. The difficulty of providing the water needed for cultivation should however be generalized to nearly all South Asian countries, given that projections for South Asia indicate a general worsening of water stress zones with a 12% increase in heat-stressed regions by 2030 (Tesfaye et al., 2017). Consequently, the future in this region will require food production with reduced water usage, promoting the adoption of VFS that save up to 95% of water compared to open-field farming (Despommier, 2010).

The findings of our study also indicate that all South Asian countries, except Nepal, are highly vulnerable to climate change. Therefore, adapting their agricultural systems to cope with external environmental conditions will be essential. Within this framework, the implementation of VFS presents an opportunity, as they enable year-round production, independent of climate variability and seasonal changes.

Next, our literature review revealed that investments and efficient support from both the private and public sectors are essential to make VF feasible, due to the particularly high costs associated with setting up a vertical farm. In this regard, our study results show that India has the best setting to adopt VFS. India's score was roughly double that of the other countries in the macro-area *Economic and Political Implications* that comprises the macro-categories *Economy and Growth*, *Private Sector*, *Financial Sector*, *Infrastructure*, *Trade*, *Aid Development Effectiveness* and *Science & Technology*. When looking more closely at the macro-categories, India has the best trade market among all South Asian countries, along with an economy, a private sector, and a financial sector that are conducive to the implementation of VF. Nepal is the country with the best financial infrastructure for developing vertical agriculture while Bhutan can rely on the strongest private sector to support the development of VF. Ultimately, the only three countries that result to be favourable in both financial and private sector macro-categories are Bhutan, India and Nepal.

Finally, the country where VF adoption seems the least feasible is Afghanistan, followed by Nepal and then Pakistan. This categorization is based on factors such as poor economic growth, an underdeveloped trade market, insufficient scientific and technical expertise, limited private and financial sector presence, and inferior social resources and infrastructure. Yet, these countries could develop and opt for simplified, low-cost and low-tech forms of VFS adapted to their specific situations. Afghanistan could also leverage the consequent international development aid it receives (best score in this macro-category) to support the research and development of vertical farms. This would notably improve the country's critical food security by providing a dependable, steady and localised supply of food through vertical farms.

At last, our empirical analysis aimed to evaluate the sustainability of VF in countries where its implementation seemed most feasible. Indeed, in the face of ongoing climate change and resource depletion driven by agriculture, only sustainable solutions should be adopted. In this regard, since only India received a “very favourable” categorisation for the feasibility analysis, only this country had a sustainability index calculated, thus preventing any comparison with other countries. Nevertheless, what we can still say is that India demonstrates greater social sustainability and lower economic sustainability in the implementation of VF. The higher social result is attributed to an outstanding score of 1 in the *Science and Technology* macro-category, indicating that India is the best positioned to create jobs rapidly and sustainably through the development of vertical farms, as it already has some of the knowledge and specialists required to implement vertical farms.

Concerning environmental sustainability, India has set a target of achieving 50% renewable energy in its energy mix by 2030 (IEA, 2022), which should further enable more sustainable food production through VF. Indeed, as we saw in the literature review, the actual environmental impact of vertical farming depends greatly on how electricity is generated (Van Delden et al., 2021).

7. Conclusion

The aim of this master's thesis was to investigate the concept of vertical farming, how it might help address some of the challenges posed by current agricultural practices, and whether it might be a feasible and sustainable solution for smallholder farmers in South Asia. Our literature review revealed that smallholder farmers form the backbone of agriculture, are of crucial importance in South Asia and yet they are confronted with significant challenges such as climate change, systematic yield gaps and the ongoing fight against hunger and poverty. In this context, vertical farming emerges as a promising solution thanks to its numerous advantages. However, our literature review highlighted several major barriers that hinder its widespread adoption.

We therefore conducted an empirical study to assess the degree of feasibility and sustainability of vertical farming for smallholders in South Asia. Our results indicated that the country where vertical farming is most feasible is India, due to its strong scientific and technological capabilities, well-developed trade markets, superior infrastructure, good urban and agricultural development, and notably better private and financial sectors compared to the other South Asian countries. Conversely, the country where vertical farming adoption seems the least feasible is Afghanistan, followed by Nepal and Pakistan. This is due to factors such as poor economic growth, an underdeveloped trade market, insufficient scientific and technical expertise, limited private and financial sector presence, and inferior social resources and infrastructure.

Regarding the sustainability of vertical farming, we have emphasized that the source of energy, especially electricity, significantly impacts its viability. To be considered an environmentally sustainable solution, vertical farms need to be powered by renewable energy sources (Al-Chalabi, 2015; Martin & Molin, 2019; Mohapatra et al., 2023).

In our opinion, while vertical farming systems could indeed provide part of the solution for smallholders in South Asia, they must be tailored to the specific socio-economic needs of each farmer and cannot be offered as a one-size-fits-all solution. They should be integrated into a broader set of strategies, both technological and non-technological, to achieve sustainable food production.

Our study encountered several limitations that we would like to highlight.

First, there is currently no established agreement on which indicators are most appropriate or pertinent for evaluating feasibility and sustainability of vertical agriculture (Paucek et al., 2023). We tried to select a wide range of indicators that we deemed most relevant, but this choice remains subjective. Additional indicators could be included in future research, sourced from other databases to which we did not have access for this thesis.

Second, we encountered a significant amount of missing data for certain specific Development Indicators and countries. This was mostly the case for Bhutan and Afghanistan. As a result, we were unable to draw conclusions for certain macro-categories for these two countries.

Third, we had data at a national level rather than at the level of smallholder farmers themselves. As a result, the findings offer a general overview of the South Asian countries' positions without directly addressing the specific circumstances of smallholders. However, given that small farms constitute 70 to 80% of all farms in South Asia (Lowder et al., 2016), we believe that our study remains valid and relevant, with results that can be applied to smallholder farmers. Nevertheless, if data at the specific scale of smallholders were to become available, it would be valuable, in future research, to conduct this analysis again using these data. This would likely allow for more refined conclusions.

Another limitation of our study is that it focused on the region of South Asia, which significantly reduced the number of countries included in the empirical analysis, thereby weakening the statistical strength of the results. A suggestion for future research would be to redo the empirical analysis but this time including all Asian countries, or at least a group comprising countries like Japan and Singapore, which already have operational vertical farms proven to be effective. This would allow for a more precise analysis of the macro-categories and macro-areas, a deeper comparison between countries and it would enable the sustainability assessment to cover several countries instead of just one, as it did in this study[21].

Concerning recommendations for future research, some have already been mentioned above but a last idea could involve contextualizing the results by examining them in relation to the historical, economic, social, and environmental backgrounds of the countries. Such an analysis was beyond the scope of this thesis, but we believe it would be valuable for providing specific recommendations for each country and thus obtain a solid basis for the feasibility study of what we feel to be a relevant, sustainable and efficient mode of production in the future.

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[21] As a reminder, India was the only country classified as “very favourable” in the feasibility analysis and therefore, a sustainability index was calculated only for this country. This did not allow for comparisons in the sustainability analysis.

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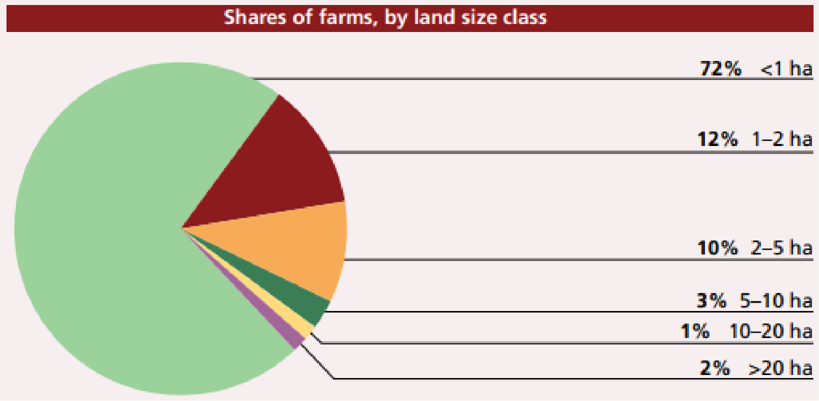
9. Appendices

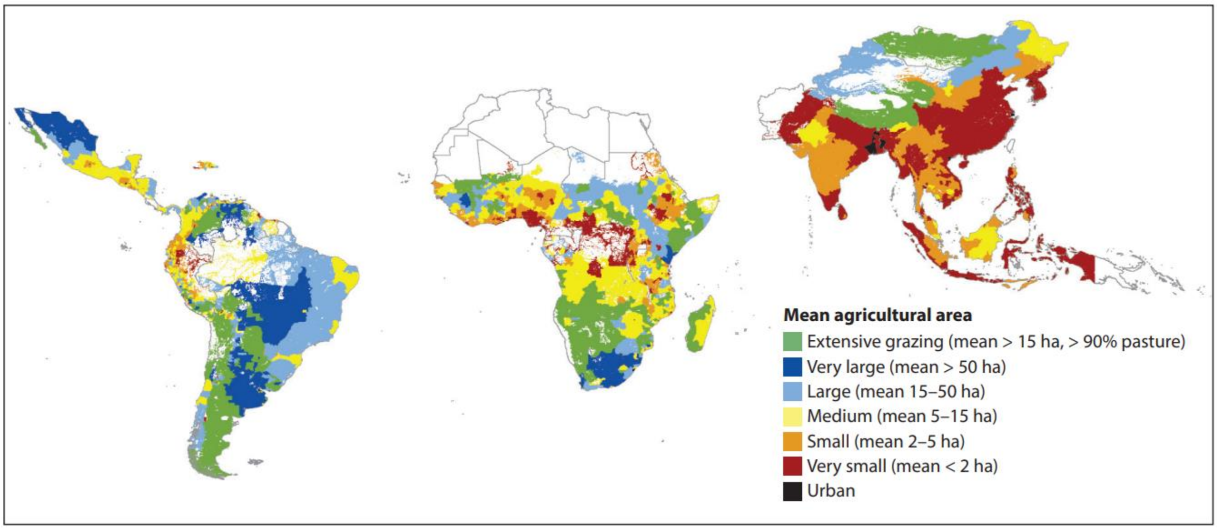
Appendix 1 | Shares of the world's farms by size.



Note: The panel shows farms by farm size covering a total of about 460 million farms in 111 countries.

Source: FAO. (2014). *The state of food and agriculture: Innovation in family farming*. Food and Agriculture Organization of the United Nations.

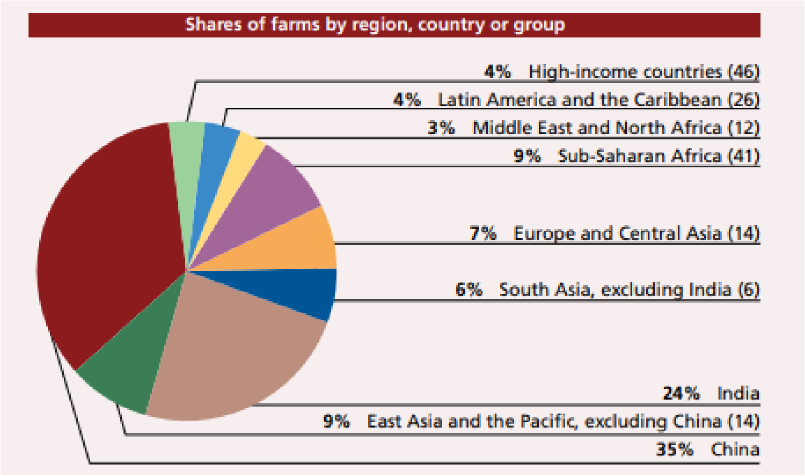
Appendix 2 | Map of average agricultural area in Central/South America, Africa and Asia.



Note: We can observe that the majority of small and very small farms are located in Asia.

Source: Cohn, A. S., Newton, P., Gil, J. D. B., Kuhl, L., Samberg, L., Ricciardi, V., Manly, J. R., & Northrop, S. (2017). Smallholder Agriculture and Climate Change. *Annual Review of Environment and Resources, 42*(1), 347–375. https://doi.org/10.1146/annurev-environ-102016-060946

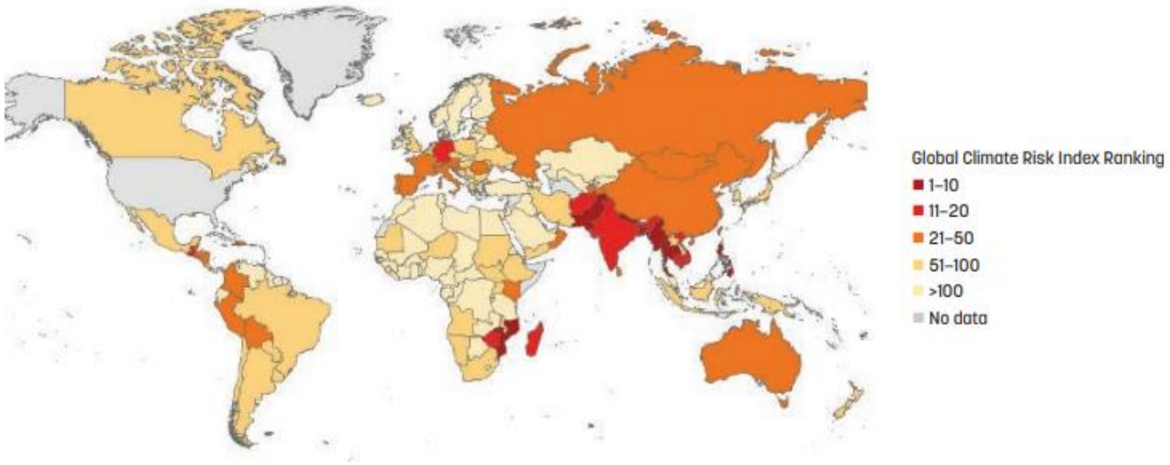
Appendix 3 | Shares of the world's farms by region.



Note: The panel is based on a sample of 161 countries, which account for almost 570 million farms; the number of countries is shown in parentheses.

Source: FAO. (2014). *The state of food and agriculture: Innovation in family farming*. Food and Agriculture Organization of the United Nations.

Appendix 4 | Global climate risk index 2021: country rankings (2000-2019).



Note: According to global climate risk index South Asia is one of the most vulnerable regions to climate risks.

Source: The World Bank Group. (2021). *Climate change action plan 2021-2025: South Asia roadmap*. https://www.worldbank.org/en/region/sar/publication/south-asia-climate-roadmap

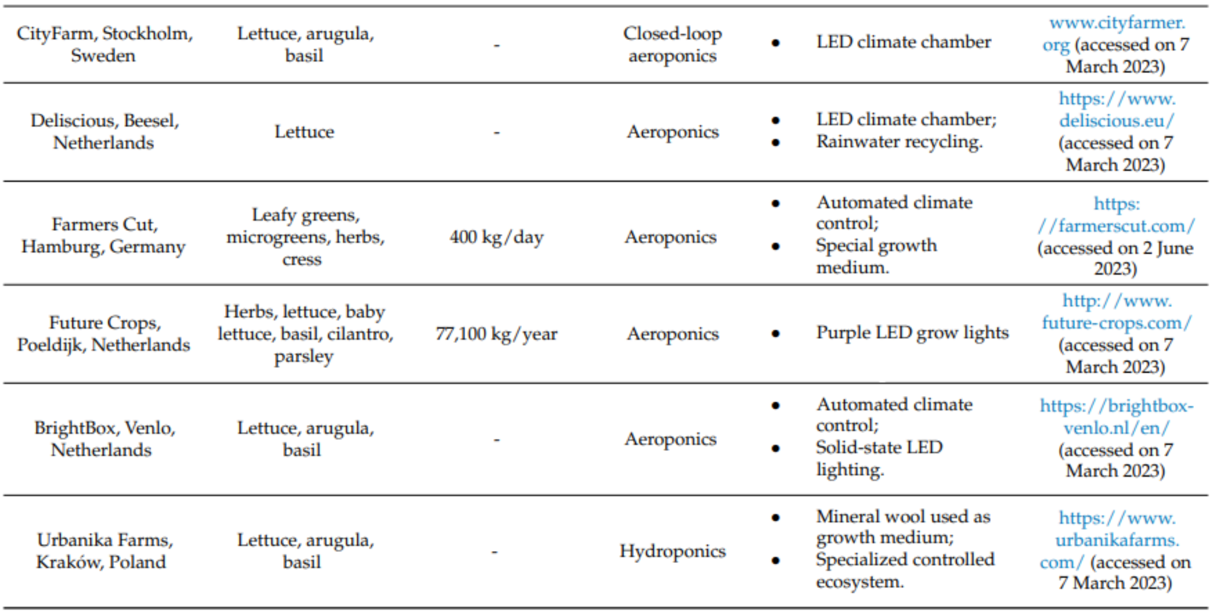
Appendix 5 | Different forms of VFS: Plants can grow vertically ((a), left) or horizontally ((b), right).

Source: Van Delden, S. H., SharathKumar, M., Butturini, M., Graamans, L. J. A., Heuvelink, E., Kacira, M., Kaiser, E., Klamer, R. S., Klerkx, L., Kootstra, G., Loeber, A., Schouten, R. E., Stanghellini, C., Van Ieperen, W., Verdonk, J. C., Vialet-Chabrand, S., Woltering, E. J., Van De Zedde, R., Zhang, Y., & Marcelis, L. F. M. (2021). Current status and future challenges in implementing and upscaling vertical farming systems. *Nature Food*, 2(12), 944–956. https://doi.org/10.1038/s43016-021-00402-w (Van Delden et al., 2021)

Appendix 6 | Leading vertical farms in production across Asia, USA and Europe.

Vertical Farm, Location	Types of Crops	Production Capacity	Cultivation System	Technical Features	Website
Shinnippo Ltd. 808 Factory, Shizuoka, Japan	Mainly lettuce (frilly, green leaf, silky, and romaine)	• First factory: 10,000 heads of lettuce daily; • Second factory: 20,000 heads of lettuce daily.	• First: DFT; • Second: NFT.	• Manual/semiautomated sowing; • Automated transplanting, packing; • Automated conveying (only in second factory).	https://www.808factory.jp/ (accessed on 7 March 2023)
Spread Co., Ltd., Kyoto, Japan	Leafy greens (lettuce), strawberries	• Techno Farm Narita: 30,000 heads of lettuce daily; • Techno Farm Fukuroi: 10 tons daily; • Kameoka Plant: 21,000 heads of lettuce daily; • Techno Farm Keihanna: 30,000 heads of lettuce daily.	DFT	• Techno Farm Keihanna • Automated cultivation utilizing IoT/AI technologies; • Technologies for environmental control and water reuse; • Specialized LED lights.	https://spread.co.jp/en/ (accessed on 7 March 2023)
Mirai Co. Ltd., Chiba, Japan	Greenleaf, kale, oakleaf, spinach, basil	• 16,000 heads of greenleaf per day	DFT	• Sensor-based monitoring and control; • Special-purpose LED.	https://miraigroup.jp/ (accessed on 7 March 2023)
N.Thing, Seoul, South Korea	Salad vegetables	• 3 tons of lettuce per cultivation module	Modular hydroponics	• Crops grown in Cube, an IoT-based container; • Developing cultivation systems and systems for new crops.	https://nthing.net/ (accessed on 10 February 2023)
NextOn, Seoul, South Korea	Special leafy vegetables (caipira, ezatrix, Isabelle), herbs, strawberries, biomaterial	• Daily output of health-functional ingredients of up to 1 ton	Smart hydroponics	• Automated lift, seeding, and transport systems; • World's largest underground vertical farm built inside an abandoned tunnel.	http://nexton.ag/farm/index.php (accessed on 7 March 2023)
Farm8, Gyeonggi-do, South Korea	Salad vegetables, special vegetables (herbs, asparagus, minivegetables, etc.)	• Collaborates with 70 farms and distributes nearly 40 tons of packaged salads daily	Hydroponics	• Shipping container-type vertical farm; • Creates vertical farms for subway stations.	http://en.farm8.co.kr/ (accessed on 10 February 2023)
SANANBIO, Fujian, China	Leafy greens, fruits, microgreens, herbs, medicinal plants, edible flowers, etc.	• Leafy greens: 400 kg/set/year (6-layer Radix); • Cucumber: 200 kg/set/year (1-layer Radix); • Microgreens: 350 kg/set/year (6-layer Radix).	NFT-DWC hybrid irrigation	• Modularized and container cultivation systems; • Utilizes a hybrid NFT and DWC system and implements customized light recipes for specialized applications.	https://www.sananbiofarm.com/ (accessed on 7 March 2023)
80 Acres Urban Agriculture limited liability company (LLC), Ohio, USA	Lettuce, rocket (arugula), kale, basil, microgreens	90,718.4 kg/year	NFT	• Closed-loop farming; • Robotics equipment is specialized for tasks like seeding, transplanting, and harvesting crops.	https://www.80acresfarms.com/ (accessed on 12 April 2023)
AeroFarms, New Jersey, USA	Baby bok choy, spinach, and micro arugula, broccoli, and kale	907,184 kg/year	Aeroponics	• Closed-loop system; • Specific light spectrum.	https://www.aerofarms.com/ (accessed on 7 March 2023)
American Hydroponics, California, USA	Leafy greens, herbs, tomatoes, peppers, cucumbers		NFT, Bato bucket, and gutter	• Seed-propagation system; • Plant-usable light system.	https://amhydro.com/ (accessed on 7 March 2023)

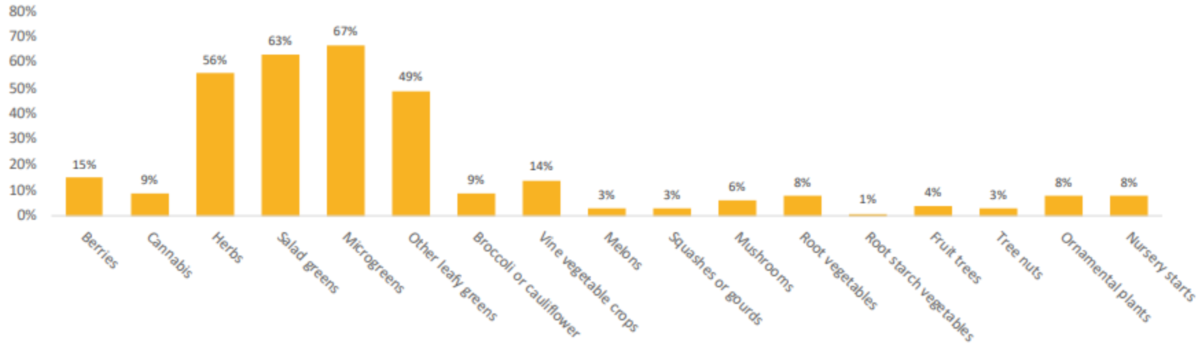
Vertical Farm, Location	Types of Crops	Production Capacity	Cultivation System	Technical Features	Website
Bright Farms, New York, USA	Lettuce, butterhead lettuce, baby spinach, basil, chickpeas		Hydroponics	• Purple LED grow lights; • Computer-controlled system.	https://www.brightfarms.com/ (accessed on 31 May 2023)
Gotham Greens, New York, USA	Lettuces, herbs	136,000 kg/year	NFT	• L1000 PPB lighting	https://www.gothamgreens.com/ (accessed on 7 March 2023)
Plenty Unlimited, California, USA	Lettuce		Hydroponics	• Watering system recycles evaporated water for plant nourishment; • Robots and conveyors transport plants between destinations.	https://www.plenty.ag/ (accessed on 26 August 2023)
Bowery Farming, New York, USA	Leafy greens, lettuce, herbs, tomatoes		Aeroponics	• Sensor- and AI-based monitoring	https://bowery.co/ (accessed on 26 August 2023)
Altius Farms, Washington, USA	Variety of leafy greens, herbs		Aeroponics	• Special grow lights	https://altiusfarms.com/ (accessed on 7 March 2023)
Green Spirit Farms, Colorado, USA	Variety of leafy greens, herbs	38,100 kg/year	Aeroponics	• LED climate chamber	https://www.greenspiritliving.com/https://altiusfarms.com/ (accessed on 7 March 2023)
PlantLab, Hertogenbosch, Netherlands	Lettuce, basil, mint, coriander, fresh-cut herbs, tomatoes	-	Aeroponics	• Specially developed LEDs	https://plantlab.com/ (accessed on 15 April 2023)
Jones Food Company, North Lincolnshire, England	Lettuce, cress, komatsuna, hazel, basil, coriander, parsley, mint, dill, rocket, strawberries	136,078 kg/year	Aeroponics	• Utilizes renewable energy; • Purple LED grow lights.	https://www.jonesfoodcompany.co.uk/ (accessed on 7 March 2023)
Agricool, Paris, France	Strawberries, basil, arugula	-	Aeroponics	• Climate-controlled containers	https://www.agritecture.com/agricool (accessed on 7 March 2023)
Infarm, Berlin, Germany	Lettuce, tomatoes, cucumbers, herbs, microgreens, mushrooms, leafy greens	-	Aeroponics	• Centrally controlled using cloud service and AI	https://www.infarm.com/ (accessed on 2 June 2023)
B-Four Agro, Warmenhuizen, Netherlands	Leafy greens, lettuce, kale, spinach	-	Aeroponics	• Solar-powered LED system; • Automated seeding.	https://b4agro.nl/ (accessed on 15 April 2023)
Byspire, Oslo, Norway	Lettuce, kale, spinach	50,000 plants/year	Aeroponics	• LED climate chamber	https://www.byspire.no/ (accessed on 7 March 2023)



CityFarm, Stockholm, Sweden	Lettuce, arugula, basil	-	Closed-loop aeroponics	- LED climate chamber	www.cityfarmer.org (accessed on 7 March 2023)
Deliscious, Beesel, Netherlands	Lettuce	-	Aeroponics	- LED climate chamber; - Rainwater recycling.	https://www.deliscious.eu/ (accessed on 7 March 2023)
Farmers Cut, Hamburg, Germany	Leafy greens, microgreens, herbs, cress	400 kg/day	Aeroponics	- Automated climate control; - Special growth medium.	https://farmerscut.com/ (accessed on 2 June 2023)
Future Crops, Poeldijk, Netherlands	Herbs, lettuce, baby lettuce, basil, cilantro, parsley	77,100 kg/year	Aeroponics	- Purple LED grow lights	http://www.future-crops.com/ (accessed on 7 March 2023)
BrightBox, Venlo, Netherlands	Lettuce, arugula, basil	-	Aeroponics	- Automated climate control; - Solid-state LED lighting.	https://brightbox-venlo.nl/en/ (accessed on 7 March 2023)
Urbanika Farms, Kraków, Poland	Lettuce, arugula, basil	-	Hydroponics	- Mineral wool used as growth medium; - Specialized controlled ecosystem.	https://www.urbanikafarms.com/ (accessed on 7 March 2023)

Source: Kabir, M. S. N., Reza, M. N., Chowdhury, M., Ali, M., Samsuzzaman, Ali, M. R., Lee, K. Y., & Chung, S.-O. (2023). Technological Trends and Engineering Issues on Vertical Farms: A Review. *Horticulturae*, 9(11), 1229. https://doi.org/10.3390/horticulturae9111229

Appendix 7 | Crops grown by operations in indoor vertical farms.



Note: The survey was carried out for indoor & controlled environment agriculture encompassing 316 participants from 54 different countries. The operations ranged from small businesses earning less than USD 10,000 annually to large enterprises with over 100 employees and annual revenues exceeding USD 10,000,000.

Source: Autogrow and Agritecture Consulting. (2019). *Global CEA Census report*. https://www.agritecture.com/census

Appendix 8 | Macro-categories and single indicators used to build the Synthetic Feasibility Index (SFI).

Synthetic Feasibility Index (SFI)			
Macro-categories	**Indicators**	**Indicator Type**	**Time Period**
Economy & Growth	Adjusted net national income (current US$)	Stimulant	2017-2021
	Adjusted net national income per capita (current US$)	Stimulant	2017-2021
	Adjusted savings: energy depletion (% of GNI)	Destimulant	2017-2021
	Adjusted savings: natural resources depletion (% of GNI)	Destimulant	2017-2021
	Agriculture, forestry, and fishing, value added (annual % growth)	Stimulant	2017-2021
	Consumer price index (2010 = 100)	Destimulant	2017-2021
	Foreign direct investment, net (BoP, current US$)	Stimulant	2017-2021
	Foreign direct investment, net inflows (BoP, current US$)	Stimulant	2017-2021
	GDP (current US$)	Stimulant	2017-2021
	GDP per capita (current US$)	Stimulant	2017-2021
	GNI (current US$)	Stimulant	2017-2021
	GNI per capita, Atlas method (current US$)	Stimulant	2017-2021
	Imports of goods and services (% of GDP)	Stimulant	2017-2021
	Imports of goods and services (BoP, current US$)	Stimulant	2017-2021
	Machinery and transport equipment (% of value added in manufacturing)	Stimulant	2017-2021
	Manufactures imports (% of merchandise imports)	Stimulant	2016-2020
	Manufacturing, value added (% of GDP)	Stimulant	2017-2021
	Net capital account (BoP, current US$)	Stimulant	2018-2022
	Net financial account (BoP, current US$)	Stimulant	2018-2022
	Net primary income (BoP, current US$)	Stimulant	2018-2022
	Net secondary income (BoP, current US$)	Stimulant	2018-2022
	Net trade in goods (BoP, current US$)	Stimulant	2018-2022
	Net trade in goods and services (BoP, current US$)	Stimulant	2018-2022
Agriculture Development	Agricultural land (% of land area)	Stimulant	2017-2021
	Agricultural land (sq. km)	Stimulant	2017-2021
	Agricultural methane emissions (% of total)	Destimulant	2004-2008
	Agricultural nitrous oxide emissions (% of total)	Destimulant	2004-2008
	Annual freshwater withdrawals, agriculture (% of total freshwater withdrawal)	Stimulant	2016-2020
	Arable land (% of land area)	Stimulant	2017-2021
	Arable land (hectares per person)	Stimulant	2017-2021
	Arable land (hectares)	Stimulant	2017-2021
	Average precipitation in depth (mm per year)	Stimulant	2016-2020

	Crop production index (2014-2016 = 100)	Stimulant	2018-2022
	Fertilizer consumption (% of fertilizer production)	Stimulant	2017-2021
	Fertilizer consumption (kilograms per hectare of arable land)	Stimulant	2017-2021
	Rural land area (sq. km)	Stimulant	2015*
	Rural population	Stimulant	2018-2022
	Rural population (% of total population)	Stimulant	2018-2022
Private sector	Cost of business start-up procedures (% of GNI per capita)	Destimulant	2015-2019
	Cost to export, border compliance (US$)	Destimulant	2015-2019
	Cost to import, border compliance (US$)	Destimulant	2015-2019
	Ease of doing business score (0 = lowest performance to 100 = best performance)	Stimulant	2015-2019
	Export unit value index (2015 = 100)	Stimulant	2017-2021
	Firms experiencing electrical outages (% of firms)	Destimulant	2007-2022*
	Firms experiencing losses due to theft and vandalism (% of firms)	Destimulant	2007-2022*
	Firms formally registered when operations started (% of firms)	Stimulant	2008-2022*
	Firms that spend on R&D (% of firms)	Stimulant	2011-2015*
	Firms using banks to finance investment (% of firms)	Stimulant	2006-2022*
	Firms using banks to finance working capital (% of firms)	Stimulant	2006-2022*
	Import unit value index (2015 = 100)	Destimulant	2017-2021
	Losses due to theft and vandalism (% of annual sales of affected firms)	Destimulant	2007-2022*
	Medium and high-tech manufacturing value added (% manufacturing value added)	Stimulant	2017-2021
	Merchandise trade (% of GDP)	Stimulant	2018-2022
	New business density (new registrations per 1,000 people ages 15-64)	Stimulant	2014-2018
	New businesses registered (number)	Stimulant	2014-2018
	Start-up procedures to register a business (number)	Destimulant	2015-2019
	Time required to enforce a contract (days)	Destimulant	2015-2019
	Time required to get electricity (days)	Destimulant	2015-2019
	Time required to obtain an operating license (days)	Destimulant	2007-2022*
	Time required to register property (days)	Destimulant	2015-2019
	Time required to start a business (days)	Destimulant	2015-2019
	Time spent dealing with the requirements of government regulations (% of senior management time)	Destimulant	2006-2022*
	Time to obtain an electrical connection (days)	Destimulant	2006-2022*
Energy	Access to electricity (% of population)	Stimulant	2017-2021
	Access to electricity, rural (% of rural population)	Stimulant	2017-2021
	Access to electricity, urban (% of urban population)	Stimulant	2017-2021
	Energy use (kg of oil equivalent per capita)	Stimulant	2010-2014

	Fossil fuel energy consumption (% of total)	Stimulant	2010-2014
	Value lost due to electrical outages (% of sales for affected firms)	Destimulant	2007-2015*
Financial sector	Domestic credit to private sector (% of GDP)	Stimulant	2016-2020
	Domestic credit to private sector by banks (% of GDP)	Stimulant	2016-2020
	Market capitalization of listed domestic companies (% of GDP)	Stimulant	2018-2022
	Market capitalization of listed domestic companies (current US$)	Stimulant	2018-2022
	Claims on private sector (annual growth as % of broad money)	Stimulant	2015-2019
Infrastructure	Electric power consumption (kWh per capita)	Stimulant	2010-2014
	Electric power transmission and distribution losses (% of output)	Destimulant	2010-2014
	Individuals using the Internet (% of population)	Stimulant	2016-2020
	Investment in energy with private participation (current US$)	Stimulant	2014-2022*
	Public private partnerships investment in energy (current US$)	Stimulant	2014-2022*
Trade	Export unit value index (2015 = 100)	Stimulant	2017-2021
	Exports of goods and services (current US$)	Stimulant	2018-2022
	High-technology exports (current US$)	Stimulant	2009-2013
	Imports of goods and services (current US$)	Stimulant	2018-2022
	Lead time to export, median case (days)	Destimulant	2007;2010;2012; 2014;2016*
	Lead time to import, median case (days)	Destimulant	2007;2010;2012; 2014;2016*
	Merchandise exports (current US$)	Stimulant	2018-2022
	Merchandise imports (current US$)	Stimulant	2018-2022
Water and Environment	Level of water stress: freshwater withdrawal as a proportion of available freshwater resources	Stimulant	2016-2020
	People using at least basic drinking water services (% of population)	Stimulant	2018-2022
	People using at least basic drinking water services, rural (% of rural population)	Stimulant	2018-2022
	People using at least basic drinking water services, urban (% of urban population)	Stimulant	2018-2022
	People using safely managed drinking water services (% of population)	Stimulant	2018-2022
	People using safely managed drinking water services, rural (% of rural population)	Stimulant	2018-2022
	People using safely managed drinking water services, urban (% of urban population)	Stimulant	2018-2022
	Plant species (higher), threatened	Destimulant	2018*
	Renewable internal freshwater resources per capita (cubic meters)	Stimulant	2016-2020
	Renewable internal freshwater resources, total (billion cubic meters)	Stimulant	2016-2020

Climate change vulnerability	Droughts, floods, extreme temperatures (% of population, average 1990-2009)	Stimulant	2009*
	Electricity production from coal sources (% of total)	Stimulant	2011-2015
	Electricity production from hydroelectric sources (% of total)	Destimulant	2011-2015
	Electricity production from natural gas sources (% of total)	Destimulant	2011-2015
	Electricity production from oil sources (% of total)	Stimulant	2011-2015
	Electricity production from oil, gas and coal sources (% of total)	Stimulant	2011-2015
	Electricity production from renewable sources, excluding hydroelectric (kWh)	Destimulant	2011-2015
	Population in urban agglomerations of more than 1 million (% of total population)	Stimulant	2019-2023
	Population, total	Stimulant	20182022
	Renewable electricity output (% of total electricity output)	Destimulant	2011-2015
	Renewable energy consumption (% of total final energy consumption)	Destimulant	2016-2020
	Total greenhouse gas emissions (kt of CO2 equivalent)	Stimulant	2016-2020
Science & Technology	Charges for the use of intellectual property, payments (BoP, current US$)	Stimulant	2016-2020
	Charges for the use of intellectual property, receipts (BoP, current US$)	Stimulant	2018-2022
	High-technology exports (current US$)	Stimulant	2008-2012
	Patent applications, residents	Stimulant	2015-2019
	Patent applications, nonresidents	Stimulant	2015-2019
	Scientific and technical journal articles	Stimulant	2016-2020
Aid development Effectiveness	Grants, excluding technical cooperation (BoP, current US$)	Stimulant	2018-2022
	Net ODA received per capita (current US$)	Stimulant	2018-2022
	Net ODA received (% of central government expense)	Stimulant	2013-2017
	Net ODA received (% of imports of goods, services and primary income)	Stimulant	2016-2020
	Net official development assistance received (current US$)	Stimulant	2018-2022
	Net official flows from UN agencies, FAO (current US$)	Stimulant	2018-2022
	Technical cooperation grants (BoP, current US$)	Stimulant	2018-2022
Social	Children in employment, total (% of children ages 7-14	Destimulant	2009-2014*
	Employment to population ratio, 15+, total (%) (modeled ILO estimate)	Stimulant	2019-2023
	GDP per person employed (constant 2021 PPP $)	Stimulant	2017-2021
	Labor force participation rate, female (% of female population ages 15+) (modeled ILO estimate)	Stimulant	2019-2023
	Labor force participation rate, male (% of male population ages 15+) (modeled ILO estimate)	Stimulant	2019-2023
	Labor force participation rate, total (% of total population ages 15+) (modeled ILO estimate)	Stimulant	2019-2023

	Labor force with advanced education (% of total working-age population with advanced education)	Stimulant	2017-2022*
	Labor force, female (% of total labor force)	Stimulant	2019-2023
	Labor force, total	Stimulant	2019-2023
	Unemployment, total (% of total labor force) (modeled ILO estimate)	Destimulant	2019-2023
	Wage and salaried workers, female (% of female employment) (modeled ILO estimate)	Stimulant	2018-2022
	Wage and salaried workers, male (% of male employment) (modeled ILO estimate)	Stimulant	2018-2022
	Wage and salaried workers, total (% of total employment) (modeled ILO estimate)	Stimulant	2018-2022
Urban development	Population density (people per sq. km of land area)	Stimulant	2017-2021
	Population in largest city	Stimulant	2019-2023
	Population in the largest city (% of urban population)	Stimulant	2019-2023
	Population in urban agglomerations of more than 1 million (% of total population)	Stimulant	2019-2023
	Urban land area (sq. km)	Stimulant	2015*
	Urban population	Stimulant	2018-2022
	Urban population (% of total population)	Stimulant	2018-2022
	Urban population growth (annual %)	Stimulant	2018-2022
Food security	Per capita food production variability (constant 2014-2016 thousand int$ per capita)	Destimulant	2016-2020
	Per capita food supply variability (kcal/cap/day)	Destimulant	2017-2021
	Prevalence of moderate or severe food insecurity in the population (%)	Destimulant	2017-2021
	Prevalence of severe food insecurity in the population (%)	Destimulant	2017-2021
	Prevalence of undernourishment (% of population)	Destimulant	2017-2021

** Indicators with data available for a specific year or arranged as data covering a long time period.*

Appendix 9 | Synthetic Feasibility Index (SFI) for each South Asian country per macro-category considered.

SYNTHETIC FEASIBILITY INDEX (SFI) PER MACRO-CATEGORY

Country	Economy and growth	Agriculture Development	Private Sector	Energy	Financial Sector	Infrastructure	Trade	Water and Environment	Climate Change Vulnerability	Science & Technology	Aid Develop. Effectiveness	Social	Urban Development	Food Security
Afghanistan	0.444	0.416	0.321	0.771	0.000	0.020	0.172	0.260	X	X	0.774	0.123	0.357	0.201
Bangladesh	0.461	0.384	0.256	0.503	0.341	0.322	0.241	0.582	0.593	0.017	0.445	0.610	0.644	0.528
Bhutan	0.512	0.261	0.679	0.977	0.728	X	0.159	0.740	X	0.000	0.264	0.683	0.278	X
India	0.519	0.583	0.592	0.845	0.737	0.692	0.820	0.537	0.749	1.000	0.274	0.478	0.639	0.748
Nepal	0.421	0.357	0.532	0.167	0.955	0.102	0.127	0.254	0.192	0.002	0.276	0.172	0.206	0.646
Pakistan	0.377	0.295	0.419	0.493	0.109	0.443	0.135	0.512	0.560	0.066	0.288	0.471	0.461	0.643
Sri Lanka	0.584	0.403	0.536	0.882	0.391	0.409	0.311	0.495	0.535	0.029	0.034	0.697	0.077	0.803

Note: A red cross is shown when there was not enough available data to calculate the synthetic index.

Appendix 10 | Synthetic measures for the distance between countries among macro-categories.

SYNTHETIC MEASURES PER MACRO-CATEGORY

Specification	Economy and growth	Agriculture Development	Private Sector	Energy	Financial Sector	Infrastructure	Trade	Water and Environment	Climate Change Vulnerability	Science & Technology	Aid Develop. Effectiveness	Social	Urban Development	Food Security
Median	0.461	0.384	0.532	0.771	0.391	0.365	0.172	0.512	0.560	0.023	0.276	0.478	0.357	0.645
Min. value	0.377	0.261	0.256	0.167	0.000	0.020	0.127	0.254	0.192	0.000	0.034	0.123	0.077	0.201
Max. value	0.584	0.583	0.679	0.977	0.955	0.692	0.820	0.740	0.749	1.000	0.774	0.697	0.644	0.803
Coefficient of variation (%)	13.516	24.951	29.382	39.999	70.149	67.269	81.446	33.406	34.738	196.671	62.563	46.691	52.272	32.995
Standard deviation	0.064	0.096	0.140	0.265	0.327	0.223	0.228	0.161	0.183	0.365	0.210	0.216	0.199	0.196
Arithmetic mean	0.474	0.386	0.476	0.662	0.466	0.331	0.280	0.483	0.526	0.186	0.336	0.462	0.380	0.595

Appendix 11 | Synthetic feasibility index (SFI) categorization per macro-category.

Macro-categories	Very favourable	Favourable	Unfavourable	Very unfavourable
	$x_j \geq \overline{x} + S_x$	$\overline{x} + S_x > x_j \geq \overline{x}$	$\overline{x} > x_j \geq \overline{x} - S_x$	$x_j < \overline{x} - S_x$
Economy and growth	≥ 0.538	0.538 to 0.474	0.474 to 0.410	< 0.410
Agriculture Development	≥ 0.482	0.482 to 0.386	0.386 to 0.289	< 0.289
Private Sector	≥ 0.616	0.616 to 0.476	0.476 to 0.336	< 0.336
Energy	≥ 0.927	0.927 to 0.662	0.662 to 0.397	< 0.397
Financial Sector	≥ 0.792	0.792 to 0.466	0.466 to 0.139	< 0.139
Infrastructure	≥ 0.554	0.554 to 0.331	0.331 to 0.108	< 0.108
Trade	≥ 0.509	0.509 to 0.280	0.280 to 0.052	< 0.052
Water and Environment	≥ 0.644	0.644 to 0.483	0.483 to 0.322	< 0.322
Climate Change Vulnerability	≥ 0.709	0.709 to 0.526	0.526 to 0.343	< 0.343
Science & Technology	≥ 0.550	0.550 to 0.186	0.186 to -0.179	< -0.179
Aid Development Effectiveness	≥ 0.547	0.547 to 0.336	0.336 to 0.126	< 0.126
Social	≥ 0.677	0.677 to 0.462	0.462 to 0.246	< 0.246
Urban Development	≥ 0.579	0.579 to 0.380	0.380 to 0.182	< 0.182
Food Security	≥0.791	0.791 to 0.595	0.595 to 0.399	< 0.399

Appendix 12 | Categorization of vertical farming feasibility per each macro-category in South Asian countries.

Categorization of vertical farming feasibility per each macro-category in South Asian countries

	Afghanistan	Bangladesh	Bhutan	India	Nepal	Pakistan	Sri Lanka
Economy and growth	unfavourable	unfavourable	favourable	favourable	unfavourable	very unfavourable	very favourable
Agriculture Development	favourable	unfavourable	very unfavourable	very favourable	unfavourable	unfavourable	favourable
Private Sector	very unfavourable	very unfavourable	very favourable	favourable	favourable	unfavourable	favourable
Energy	favourable	unfavourable	very favourable	favourable	very unfavourable	unfavourable	favourable
Financial Sector	very unfavourable	unfavourable	favourable	favourable	very favourable	very unfavourable	unfavourable
Infrastructure	very unfavourable	unfavourable	x	very favourable	very unfavourable	favourable	favourable
Trade	unfavourable	unfavourable	unfavourable	very favourable	unfavourable	unfavourable	favourable
Water and Environment	very unfavourable	favourable	very favourable	favourable	very unfavourable	favourable	favourable
Climate Change Vulnerability	x	favourable	x	very favourable	very unfavourable	favourable	favourable
Science & Technology	x	unfavourable	unfavourable	very favourable	unfavourable	unfavourable	unfavourable
Aid Develop. Effectiveness	very favourable	favourable	unfavourable	unfavourable	unfavourable	unfavourable	very unfavourable
Social	very unfavourable	favourable	very favourable	favourable	very unfavourable	favourable	very favourable
Urban Development	unfavourable	very favourable	unfavourable	very favourable	unfavourable	favourable	very unfavourable
Food Security	very unfavourable	unfavourable	x	favourable	favourable	favourable	very favourable

Appendix 13 | Categorization of the feasibility of vertical farming for each of the 14 macro-categories in South Asian countries.

Economy and Growth

Agriculture Development

Private sector

Energy

Financial sector

Infrastructure

Trade

Water and Environment

Climate Change Vulnerability

Science and Technology

Aid Development Effectiveness

Social

Urban development

Food security

Vertical farming Macro-category feasibility

- 🟩 Very favourable
- 🟩 Favourable
- 🟧 Unfavourable
- 🟥 Very unfavourable

Note: *Generated with MapChart (https://www.mapchart.net/).*

Appendix 14 | Synthetic Feasibility Index (SFI) for each South Asian country per macro-area considered.

SYNTHETIC FEASIBILITY INDEX PER MACRO-AREA

Country	Urban agriculture productivity and Food security	Economic and Political implications	Resource availability and social implication
Afghanistan	0.325	0.288	0.384
Bangladesh	0.537	0.297	0.565
Bhutan	0.269	0.390	0.800
India	0.680	0.662	0.620
Nepal	0.350	0.345	0.198
Pakistan	0.490	0.262	0.492
Sri Lanka	0.454	0.327	0.691

Appendix 15 | Synthetic measures for the distance between countries among macro-areas.

SYNTHETIC MEASURES PER MACRO-AREA

Specification	Urban agriculture productivity and Food security	Economic and Political implications	Resource availability and social implication
Median	0.454	0.327	0.565
Min. value	0.269	0.262	0.198
Max. value	0.680	0.662	0.800
Coefficient of variation (%)	29.520	34.338	34.630
Standard deviation	0.131	0.126	0.186
Arithmetic mean	0.444	0.368	0.536

Appendix 16 | Synthetic feasibility index (SFI) categorization per macro-area.

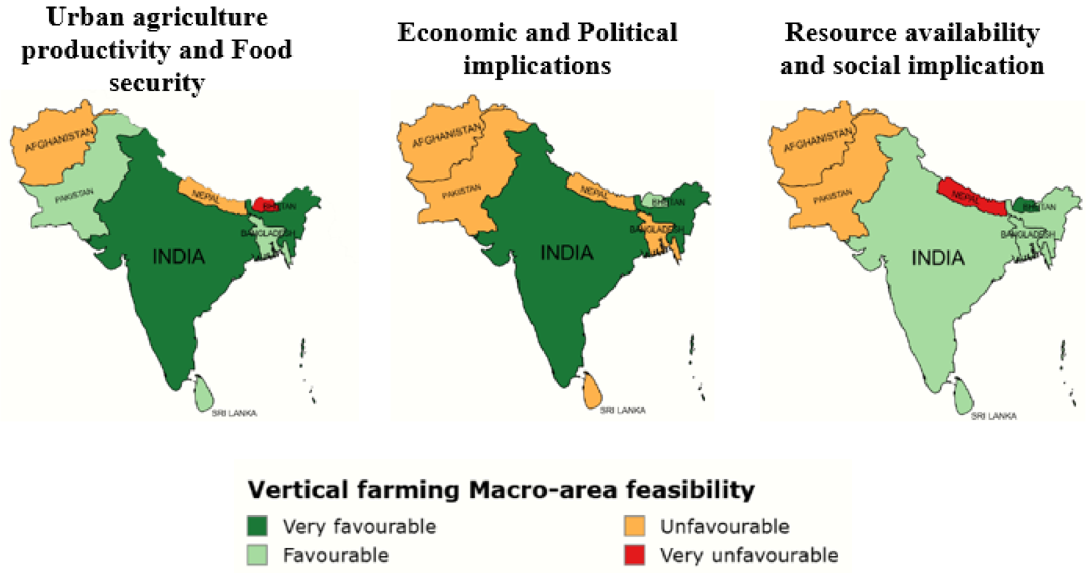
Macro-areas	Very favourable	Favourable	Unfavourable	Very unfavourable
	$x_j \geq \bar{x} + S_x$	$\bar{x} + S_x > x_j \geq \bar{x}$	$\bar{x} > x_j \geq \bar{x} - S_x$	$x_j < \bar{x} - S_x$
Urban agriculture productivity and Food security	≥ 0.575	0.575 to 0.444	0.444 to 0.313	< 0.313
Economic and Political implications	≥ 0.494	0.494 to 0.368	0.368 to 0.241	< 0.241
Resource availability and social implication	≥ 0.721	0.721 to 0.536	0.536 to 0.350	< 0.350

Appendix 17 | Categorization of vertical farming feasibility per each macro-area in South Asian countries.

Categorization of vertical farming feasibility per each macro-area in South Asian countries

Country	Urban agriculture productivity and Food security	Economic and Political implications	Resource availability and social implication
Afghanistan	unfavourable	unfavourable	unfavourable
Bangladesh	favourable	unfavourable	favourable
Bhutan	very unfavourable	favourable	very favourable
India	very favourable	very favourable	favourable
Nepal	unfavourable	unfavourable	very unfavourable
Pakistan	favourable	unfavourable	unfavourable
Sri Lanka	favourable	unfavourable	favourable

Appendix 18 | Categorization of the feasibility of vertical farming for the 3 macro-areas in South Asian countries.

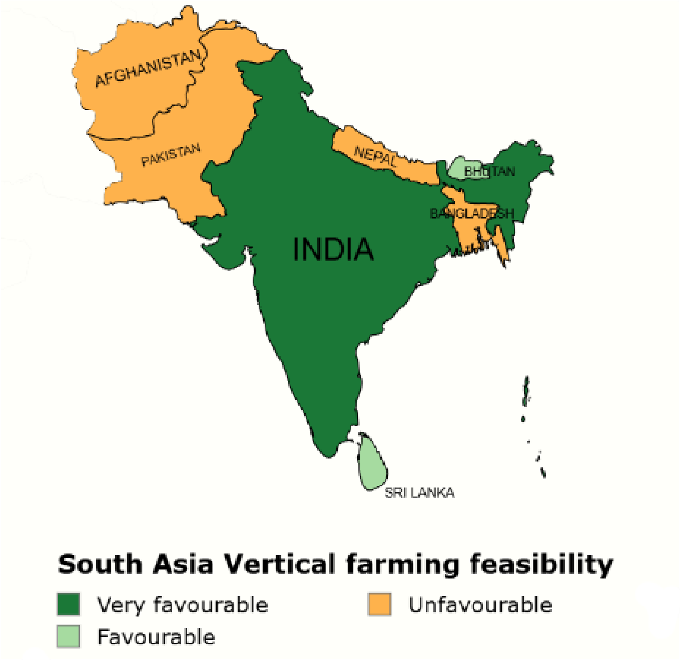


Note: *Generated with MapChart (https://www.mapchart.net/).*

Appendix 19 | Categorization of vertical farming general feasibility in South Asian countries.

FINAL SYNTHETIC FEASIBILITY INDEX (SFI)			
Country	**Position**	**Vertical farming feasibility**	**Categorization**
India	**1**	0.699	very favourable
Sri Lanka	**2**	0.434	favourable
Bhutan	**3**	0.410	favourable
Bangladesh	**4**	0.394	unfavourable
Pakistan	**5**	0.348	unfavourable
Nepal	**6**	0.297	unfavourable
Afghanistan	**7**	0.284	unfavourable

Appendix 20 | Categorization of the feasibility of vertical farming in South Asian countries.



Note: Generated with MapChart (https://www.mapchart.net/).

Appendix 21 | Macro-categories and single indicators of development used to build the Synthetic Sustainability Index (SSI).

Synthetic Sustainability Index (SSI)

	Macro-categories	Indicators	Indicator Type	Time Period
ENVIRONMENTAL SUSTAINABILITY	Energy	Access to electricity (% of population)	Stimulant	2017-2021
		Access to electricity, rural (% of rural population)	Stimulant	2017-2021
		Access to electricity, urban (% of urban population)	Stimulant	2017-2021
		Energy use (kg of oil equivalent per capita)	Stimulant	2010-2014
		Fossil fuel energy consumption (% of total)	Stimulant	2010-2014
		Value lost due to electrical outages (% of sales for affected firms)	Destimulant	2007-2015*
	Water and Environment	Level of water stress: freshwater withdrawal as a proportion of available freshwater resources	Stimulant	2016-2020
		People using at least basic drinking water services (% of population)	Stimulant	2018-2022
		People using at least basic drinking water services, rural (% of rural population)	Stimulant	2018-2022
		People using at least basic drinking water services, urban (% of urban population)	Stimulant	2018-2022
		People using safely managed drinking water services (% of population)	Stimulant	2018-2022
		People using safely managed drinking water services, rural (% of rural population)	Stimulant	2018-2022
		People using safely managed drinking water services, urban (% of urban population)	Stimulant	2018-2022
		Plant species (higher), threatened	Destimulant	2018*
		Renewable internal freshwater resources per capita (cubic meters)	Stimulant	2016-2020
		Renewable internal freshwater resources, total (billion cubic meters)	Stimulant	2016-2020
ECONOMIC SUSTAINABILTY	Economy & Growth	Adjusted net national income (current US$)	Stimulant	2017-2021
		Adjusted net national income per capita (current US$)	Stimulant	2017-2021
		Adjusted savings: energy depletion (% of GNI)	Destimulant	2017-2021
		Adjusted savings: natural resources depletion (% of GNI)	Destimulant	2017-2021
		Agriculture, forestry, and fishing, value added (annual % growth)	Stimulant	2017-2021
		Consumer price index (2010 = 100)	Destimulant	2017-2021
		Foreign direct investment, net (BoP, current US$)	Stimulant	2017-2021
		Foreign direct investment, net inflows (BoP, current US$)	Stimulant	2017-2021
		GDP (current US$)	Stimulant	2017-2021
		GDP per capita (current US$)	Stimulant	2017-2021
		GNI (current US$)	Stimulant	2017-2021
		GNI per capita, Atlas method (current US$)	Stimulant	2017-2021

		Imports of goods and services (% of GDP)	Stimulant	2017-2021
		Imports of goods and services (BoP, current US$)	Stimulant	2017-2021
		Machinery and transport equipment (% of value added in manufacturing)	Stimulant	2017-2021
		Manufactures imports (% of merchandise imports)	Stimulant	2016-2020
		Manufacturing, value added (% of GDP)	Stimulant	2017-2021
		Net capital account (BoP, current US$)	Stimulant	2018-2022
		Net financial account (BoP, current US$)	Stimulant	2018-2022
		Net primary income (BoP, current US$)	Stimulant	2018-2022
		Net secondary income (BoP, current US$)	Stimulant	2018-2022
		Net trade in goods (BoP, current US$)	Stimulant	2018-2022
		Net trade in goods and services (BoP, current US$)	Stimulant	2018-2022
	Urban development	Population density (people per sq. km of land area)	Stimulant	2017-2021
		Population in largest city	Stimulant	2019-2023
		Population in the largest city (% of urban population)	Stimulant	2019-2023
		Population in urban agglomerations of more than 1 million (% of total population)	Stimulant	2019-2023
		Urban land area (sq. km)	Stimulant	2015*
		Urban population	Stimulant	2018-2022
		Urban population (% of total population)	Stimulant	2018-2022
		Urban population growth (annual %)	Stimulant	2018-2022
SOCIAL SUSTAINABILITY	**Science & Technology**	Charges for the use of intellectual property, payments (BoP, current US$)	Stimulant	2016-2020
		Charges for the use of intellectual property, receipts (BoP, current US$)	Stimulant	2018-2022
		High-technology exports (current US$)	Stimulant	2008-2012
		Patent applications, residents	Stimulant	2015-2019
		Patent applications, nonresidents	Stimulant	2015-2019
		Scientific and technical journal articles	Stimulant	2016-2020
	Social	Children in employment, total (% of children ages 7-14	Destimulant	2009-2014*
		Employment to population ratio, 15+, total (%) (modeled ILO estimate)	Stimulant	2019-2023
		GDP per person employed (constant 2021 PPP $)	Stimulant	2017-2021
		Labor force participation rate, female (% of female population ages 15+) (modeled ILO estimate)	Stimulant	2019-2023
		Labor force participation rate, male (% of male population ages 15+) (modeled ILO estimate)	Stimulant	2019-2023
		Labor force participation rate, total (% of total population ages 15+) (modeled ILO estimate)	Stimulant	2019-2023
		Labor force with advanced education (% of total working-age population with advanced education)	Stimulant	2017-2022*
		Labor force, female (% of total labor force)	Stimulant	2019-2023
		Labor force, total	Stimulant	2019-2023

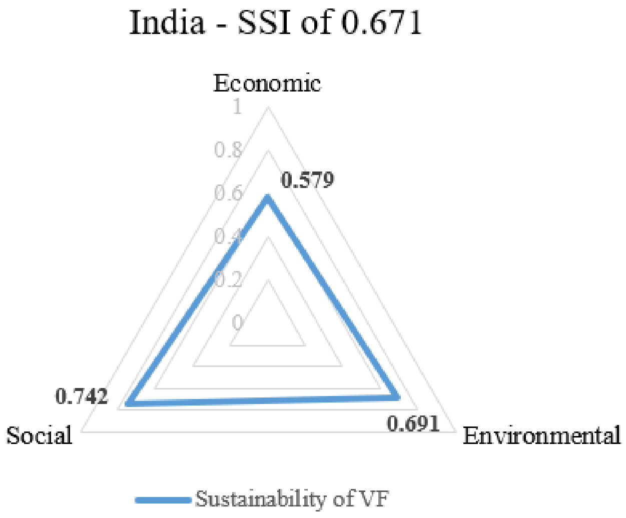
	Unemployment, total (% of total labor force) (modeled ILO estimate)	Destimulant	2019-2023
	Wage and salaried workers, female (% of female employment) (modeled ILO estimate)	Stimulant	2018-2022
	Wage and salaried workers, male (% of male employment) (modeled ILO estimate)	Stimulant	2018-2022
	Wage and salaried workers, total (% of total employment) (modeled ILO estimate)	Stimulant	2018-2022
Food Security	Per capita food production variability (constant 2014-2016 thousand int$ per capita)	Destimulant	2016-2020
	Per capita food supply variability (kcal/cap/day)	Destimulant	2017-2021
	Prevalence of moderate or severe food insecurity in the population (%)	Destimulant	2017-2021
	Prevalence of severe food insecurity in the population (%)	Destimulant	2017-2021
	Prevalence of undernourishment (% of population)	Destimulant	2017-2021

** Indicators with data available for a specific year or arranged as data covering a long time period.*

Appendix 22 | Synthetic Sustainability Index (SSI) for India according to the three pillars of sustainability.

SYNTHETIC SUSTAINABILITY INDEX			
Country	**Economic sustainability**	**Environmental sustainability**	**Social sustainability**
India	0.579	0.691	0.742

Appendix 23 | Assessment of the economic, social and environmental sustainability of vertical farming for India.



Appendix 24 | List of indicators for which data were missing.

Country	Indicators for which data were missing
Afghanistan	• Machinery and transport equipment (% of value added in manufacturing) • Energy use (kg of oil equivalent per capita) • Fossil fuel energy consumption (% of total) • Market capitalization of listed domestic companies (% of GDP) • Market capitalization of listed domestic companies (current US$) • Electric power consumption (kWh per capita) • Electric power transmission and distribution losses (% of output) • High-technology exports (current US$) • Electricity production from coal sources (% of total) • Electricity production from hydroelectric sources (% of total) • Electricity production from natural gas sources (% of total) • Electricity production from oil sources (% of total) • Electricity production from oil, gas and coal sources (% of total) • Electricity production from renewable sources, excluding hydroelectric (kWh) • High-technology exports (current US$) • Patent applications, residents • Patent applications, nonresidents
Bangladesh	• Manufactures imports (% of merchandise imports)
Bhutan	• Machinery and transport equipment (% of value added in manufacturing) • Manufactures imports (% of merchandise imports) • Fertilizer consumption (% of fertilizer production) • Medium and high-tech manufacturing value added (% manufacturing value added) • Energy use (kg of oil equivalent per capita) • Fossil fuel energy consumption (% of total) • Market capitalization of listed domestic companies (% of GDP) • Market capitalization of listed domestic companies (current US$) • Electric power consumption (kWh per capita) • Electric power transmission and distribution losses (% of output) • Investment in energy with private participation (current US$) • Public private partnerships investment in energy (current US$) • Lead time to export, median case (days) • Lead time to import, median case (days) • Electricity production from coal sources (% of total) • Electricity production from hydroelectric sources (% of total) • Electricity production from natural gas sources (% of total) • Electricity production from oil sources (% of total) • Electricity production from oil, gas and coal sources (% of total) • Electricity production from renewable sources, excluding hydroelectric (kWh) • Population in urban agglomerations of more than 1 million (% of total population) • Children in employment, total (% of children ages 7-14) • Population in largest city

	• Population in the largest city (% of urban population) • Population in urban agglomerations of more than 1 million (% of total population) • Per capita food supply variability (kcal/cap/day) • Prevalence of moderate or severe food insecurity in the population (%) • Prevalence of severe food insecurity in the population (%) • Prevalence of undernourishment (% of population)
India	• People using safely managed drinking water services (% of population) • People using safely managed drinking water services, urban (% of urban population) • Prevalence of moderate or severe food insecurity in the population (%) • Prevalence of severe food insecurity in the population (%)
Nepal	• Fertilizer consumption (% of fertilizer production) • Market capitalization of listed domestic companies (% of GDP) • Market capitalization of listed domestic companies (current US$) • Charges for the use of intellectual property, payments (BoP, current US$) • Charges for the use of intellectual property, receipts (BoP, current US$)
Pakistan	• Net ODA received (% of central government expense)
Sri Lanka	• Charges for the use of intellectual property, payments (BoP, current US$) • Charges for the use of intellectual property, receipts (BoP, current US$) • Population in urban agglomerations of more than 1 million (% of total population)

Abstract :

In this master’s thesis, titled “*Is vertical farming a relevant and feasible solution for sustainable agriculture among smallholders in South Asia?*”, we investigate the concept of vertical farming, how it might help address some of the challenges posed by current agricultural practices, and whether it might be a feasible and sustainable solution for smallholder farmers in South Asia.

Considering that vertical farming is an innovative method gaining momentum globally, with the potential to provide an efficient and sustainable food production system for smallholders in South Asia, this thesis aims to offer valuable insights on the subject.

After describing the concepts of smallholders and vertical farming systems, we discussed the conditions required for the successful implementation of vertical farms. This led to our empirical analysis, in which we assessed the degree of feasibility, and hence sustainability, of vertical farming in seven South Asian countries: Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan, and Sri Lanka.

Our results revealed that the country demonstrating the best prospective for vertical farming implementation is India, followed by Sri Lanka and Bhutan, while the countries where vertical farming adoption seems the least feasible are Afghanistan, Nepal and Pakistan. We finished by discussing the implications of these results for the countries.

In this master’s thesis, we therefore show that vertical farming deserves serious consideration in India as a solution to the challenges currently faced by agriculture.

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