Novel Materials for Urban Farming

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Abstract. Scarcity of natural resources, shifting demographics, climate change and increasing waste are four major challenges in our quest to feed the exploding world population. These challenges serve as the impetus for us to harness novel technologies to improve our agriculture, productivity and sustainability. Urban farming has several advantages over conventional farming: higher productivity, improved sustainability and the ability to provide fresh food all year round. Novel materials are key to accelerating the evolution of urban farming – with their ability to facilitate controlled release of nutrients and pesticides, improved seed health, substrates with better water retention capability, more efficient recycling of agricultural waste, and precise plant health monitoring. Advances in materials science will enable environmental sustainability and higher harvest yields in urban farms. In this review, Singapore is used as an example of a land-scarce city where urban farming may be the solution for future food production. Potential research directions and challenges in urban farming are highlighted, and we briefly discuss how materials optimization and innovation will drive the development of urban farming to meet national and global food demands. This review serves as a guide for

academic researchers and a reference for stakeholders of urban farms, policy makers and other interested parties.

1. Introduction

The world population stands at ~7.8 billion today and is expected to increase to ~9.6 billion by 2050. Such an increase implies that our current food production rate needs to be increased by 70% to meet the global demand.[1] This is an ambitious target that cannot be achieved given that the current expansion rate of agricultural land lags significantly behind the population growth rate (**Figure 1**a). The implication is that 660 million people will face hunger in 2030, and this number will continue to grow.[2] Conventional food production – which relies heavily on agriculture and animal husbandry, is putting huge strains on our environment both in terms of land use and sustainability.

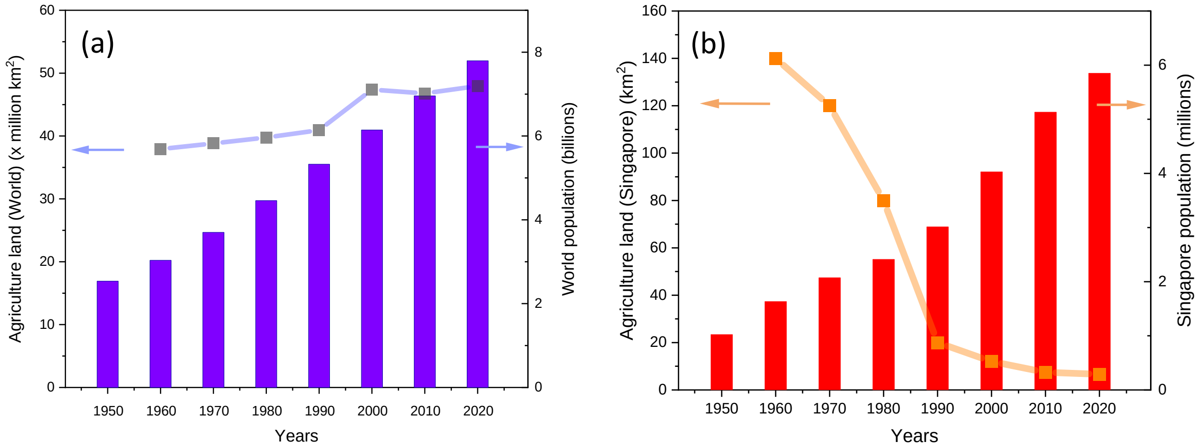

Figure 1. Population growth and agriculture land changes over the years since 1950. a) World and b) Singapore population growth and the corresponding agriculture land area. Data obtained from United Nations database.[1] Note: the agricultural land area for both the world and Singapore for 1960 is not available so values for 1961 are shown, likewise areas for 2020 have been substituted by 2018 areas.

Due to the proliferation of urban cities and development to provide the economic growth necessary to support the growing population, agricultural farmland is shrinking in terms of the population supported per square kilometre of agricultural land. For land-scarce cities like Singapore, Hong Kong and New York City, this is especially glaring. Taking Singapore as an example, while its population is growing, the agricultural land has shrunk substantially (Figure 1b). Meeting the Singapore governmental target of producing 30% of the nation's food requirement by 2030 (30-by-30 goal) is therefore a huge challenge with the limited availability of arable land. The situation has been worsened by the prevailing spread of COVID-19, which has impeded international food trading.

Urban farms can be located both indoors and outdoors.[3-6] Some examples are vertical farming, greenhouse farming, container farming, rooftop farming, spared field farming, and warehouse farming. Vertical farming can exist in the form of either soil-based farming or soilless farming, such as hydro-, aqua- or aeroponics. High-rise commercial and residential buildings with integrated indoor farming and rooftop farming are gaining a lot of traction. On top of this, edible landscapes and community farms are also contributing to the changing agriculture landscape. The advantage of embedding food production into the urban landscape is that it provides an opportunity for more sustainable and environmentally friendly food distribution due to the proximity of food production and consumers. This improves the carbon footprint and reduces food wastage during transportation. Urban farms also provide the potential for integrating farm requirements for space (via building integration), water, energy and waste recycling into the resource stream in the city.[7] There are many opportunities to make use of novel materials in urban farming which can contribute to building a higher productivity and more sustainable urban farms (**Figure 2**).

Figure 2. Different types of urban farming and the use of novel materials in the various aspects of plant growth.

Conventional farming practices may or may not be directly applied to urban farming since some additional requirements such as precise management of environmental conditions may be required for the latter.[8-11] In urban farming, there is an opportunity and a requirement of "smartness" in the delivery plants or crop needs such as detailed nutrient monitoring, pesticide management, and fast-response environmental feedback and control. The increasing burden that farming systems place on our limited resources renders sustainable food production an important consideration in urban farming, with the goal of feeding the growing population with minimum impact on the environment. As a result of these challenges, innovative technological approaches are required to improve the sustainability and productivity of urban farms. Materials that allow for controlled or stimuli- triggered release of nutrients and pesticides, materials that help to improve seed health, water retention ability of substrates, recycling of agricultural waste, materials for environmental control and plant health monitoring are all important aspects in which there have been promising developments and potential for more disruptive technologies.

Based on what is needed in the future agriculture landscape, some classes of materials can be identified that can transform agriculture in a positive way and at the same time address the world needs for more food. Functional materials, nanostructured materials, smart materials (stimuli responsive materials) made of polymers and oxide- or non-oxide-based inorganics are materials with huge potential in agriculture (**Figure 3**). These materials are especially important in the urban farming context as improvements in urban food production should not increase substantially the energy or water consumption or exert a negative impact on the environment.

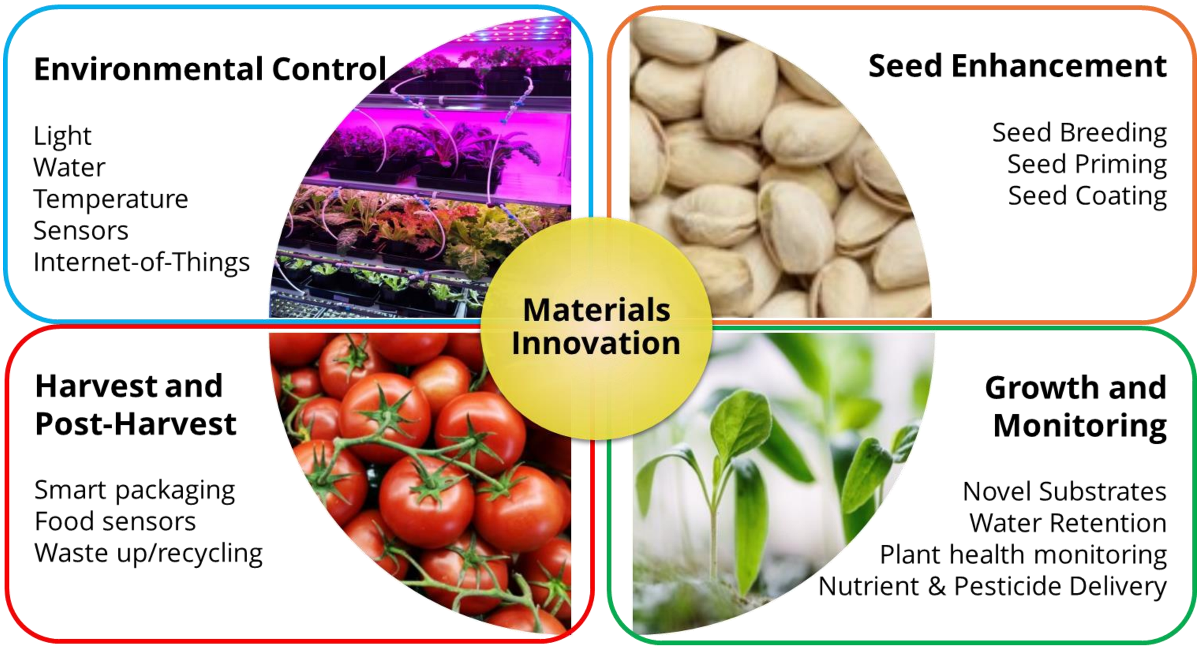

Figure 3. Materials technology contribution to the whole plant cultivation cycle.

Nanostructured materials have been used particularly to tailor the delivery of nanofertilizers, nano-biosensors and nanopesticides for improving plant growth.[12, 13] They have also been used as novel substrates for soil replacement for weight reduction which is one important consideration for roof top farming. There are other materials whose function does not directly impact plant growth, but instead are essential to support the ecosystem needed for urban farming. Novel functional materials such as perovskites as light-emitting diode materials, are also gaining huge momentum that will serve to impact the lighting design in indoor farming sector.[14] Phase change, thermochromic and other materials that can help with temperature management is another important area for consideration.[15] Polymeric materials have also gained significant traction in agriculture.[16, 17] They are extremely versatile as their properties such as structure, functionality, and biodegradability can be specially designed and controlled with the right materials chemistry. In recent years, the focus has been on stimuli-responsive smart polymeric materials and in some cases with bespoke functionality for plant application.[17] This has led to novel materials in the controlled delivery of nutrients and pesticide, soil conditioning and water delivery, waste management and many other areas.

Materials science has contributed substantially to civilization development. The first to the fourth industrial revolutions are all driven by materials development. Novel materials have consistently been shown to impact many areas such as energy and optoelectronics.[18-20] There is much potential in the exploration of novel materials for traditional areas such as farming. Moving into the near future, to ensure that urban farming becomes an integral part of food production in the world and in land-scarce cities such as Singapore, there are materials technological developments that will pave the way - the Internet-of-Things (IoT) enabled by sensors using novel materials,[21-24] upcycling of agriculture waste[25-28] to ensure circularity in the materials used, and data science driven new materials design for better plant interaction[29, 30] and more bespoke applications.[31, 32] Although there is literature that discusses nanomaterials and polymers for agriculture, to the best of our knowledge, there is no comprehensive review on the use of novel materials for urban farming. In this review, we set out to assess the potential impacts that novel materials have brought to agriculture and discuss why this area will gain more traction among researchers and policy makers in the future. We have shared the vision on how the use of novel materials in urban farming can transform food production landscape. It is certainly our hope that in 2050, new material technologies will bring us closer to feeding most of the world's population with little impact on climate conditions, environmental ecosystems and resource availability.

2. Novel Materials Concepts for Urban Farming

Urban farming has been gaining momentum in the past decade as one of the possible strategies to empower the future food production landscape. It shares a few common features with conventional farming but carries advantages such as high productivity, improved sustainability, a small space requirement (vertical farming and farms integrated into buildings), the ability to provide fresh food all-year-round, and a simple process (in the case of small plot farming or community gardens). Novel materials applications such as nanostructured fertilizer, pesticides, soilless substrate, water retention materials, light sources (LED or laser), light and temperature management materials (phase change materials, thermochromic materials, cooling coatings), plant health monitoring systems and waste management will have a significant influence on the future development of urban farming. In this section, we will focus on these materials and their importance in urban farming.

2.1. Seed Enhancement

To improve the efficiency and economics of urban farming, one can optimize the environmental factors, (e.g., lighting and temperature control) and logistic factors for farm plant operation, harness automation and make use of intelligent nutrient and pesticide delivery. Another approach is to breed seeds which can adapt to supplemental light, controlled temperature variation and intensive growth conditions. However, most of the current available seed technology is adapted to outdoor agriculture or greenhouses which have a good supply of sunlight and water, employ soil substrates for plant growth, and are supported by adequate nutrients and pesticides.[33, 34] Outdoor plants can survive droughts, floods, insects and other adverse conditions to some degree. In the field, phenotypic stability is paramount, as production must be consistent in an unpredictable and changing environment.[34] In controlled environments, (e.g., greenhouses or indoor farms), plants have sufficient water supply, temperature control, an isolated clean environment and the possibility of intensive monitoring or sensing systems. Environmental flux, pests, pathogens and post-harvest quality which are critical barriers to production for outdoor farming are well-managed for controlled environmental farming. Taste, colour, and nutrient improvements are important and become value-added factors. They should be bred to maximise genetic plasticity, allowing specific traits to be present as a function of the quality of the ambient light spectrum[35] and for ease of handling during seedling transplantation and harvest. For this aspect, biological materials modification is critical and this can be in the form of genome editing to change plants' characteristics so that they are more sustainable, exhibit desired traits, and fit the constraints of the controlled environments.[36] In contrast to traditional selective breeding, which depends on the feasibility of plant population and spontaneous or artificial-induced low chance mutations, genome editing as an advanced molecular biology technique can produce precisely targeted modifications. For example, a combination of base editing and DNA-free genome editing has been described in wheat,[37] with average frequencies of cytidine to thymidine (C-to-T) conversion of 1.8% at two sites. The combination of DNA-free genome editing and base editing can greatly facilitate plant breeding and the commercialization of edited plants. It has the potential to meet the seed demands of emerging urban farm systems. One recent study used RNA viruses to deliver gene-editing reagents to the germ line through infected plants and create hundreds to thousands of diverse mutations in the progeny of infected plants.[38, 39] The authors showed that when RNA sequences that promote cell-to-cell movement are fused to the sgRNAs, heritable gene edits are recovered at high frequency. Mutant progenies are recovered in the next generation at frequencies ranging from 65 to 100%; up to 30% of progeny derived from plants infected with a virus expressing three sgRNAs have mutations in all three targeted loci.

They found that most of the seed harvested from infected plants carried one or more gene edits. Recently, there has been progress in designing nanomaterials to deliver genes to wild-type plants for plant genetic engineering applications.[40, 41] Inorganic materials can be coated with positively charged polymers which electrostatically bind and protect DNA for delivery into plant cells. These nanocarriers can be engineered to target different subcellular compartments within the mesophyll cell, as well as plant organs such as pollen grains.[41-44] If the genetic modifications enabled by these methods can be inherited by the progeny, nanoparticle-mediated approaches can accelerate plant engineering in a species-independent manner which remains a major bottleneck with existing approaches.[45]

Seed quality plays an important role in successful crop cultivation regardless of whether it is conventional or urban farming. High-quality seeds with enhanced vigour contribute to nearly 30% of total production. Nowadays, researchers, farmers and governments recognize the importance of seed production and supply in advancing food production. Besides seed breeding, seeds can be treated in several ways prior to planting to ensure better quality and yield potential of the crops. Seed quality enhancement aims to improve the hygiene and mechanical properties of the seed, breaking their dormancy and subsequently facilitating synchronized germination, ensuring equal distribution of the nutrients and imparting stress tolerance. It refers to a mixture of technologies which primarily include seed priming, physical stimulation, seed pelleting, and coating.[46, 47]

2.1.1. Seed Priming

Seed priming is the hydration of seeds under controlled conditions before sowing, and this is done to the point where seeds begin the germination process but are redried before germination proceeds to the point of radicle or epicotyl extension.[48-50]. It can reduce the variability in seed germination rate within a population, ensuring more uniform and rapid germination and establishment.[51, 52] It can also confer greater resilience to thermal, moisture and osmoticum (salt) stresses,[53] and this is therefore beneficial for plant establishment in harsh environment.[54] Methods of seed priming can be hydropriming, osmotic priming, halo priming, matrix priming, nano-priming and bio-priming. The most conventional form of seed priming is hydropriming whereby seeds are usually soaking in water or priming solution followed by drying prior to sowing. Osmotic priming is a method in which seeds are soaked in an osmotic solution such as polyethylene glycol or mannitol.[55] Halo priming is a priming process where seeds are treated with salt solution to improve germination and increase salinity tolerance. Solid matrix priming is an approach in which seeds are mixed with a solid, insoluble matrix (e.g., compost, clay, peat, sand, vermiculite, or water-absorbent polymer) that is moistened with a limited amount of water for priming.[56] It is found to be more effective than osmotic priming because the process is thought to simulate natural seedbed conditions and oxygen is freely available to seeds throughout the duration of priming. Solid matrix priming has demonstrated positive results for both horticultural and wild plant species[57] and has the potential to be combined with other seed enhancement technologies.[47]

Material contribution to matrix, nano- and biopriming is most significant amongst all the priming methods. A few seeds could be placed together in extruded pods using machinery for making pastas and pastries.[58] Pods are formed by creating a "dough" containing seeds, various clay filler materials, absorbents, bio-stimulants, plant protectants, water and other desired ingredients and then running the mixture through an extruder that forms and cuts the extruded material into desired shapes.[47, 59] The authors demonstrated how solid matrix priming (-0.5 to -2.5 MPa for up to 12 days) can be effectively combined with seed coating technologies (e.g., seed "pods") to improve emergence and establishment density of two grass species.[57] The emergence from the primed seed pods was 66–82% faster than for non-treated seeds. Additionally, the final density of *P. spicata* seedlings originating from primed-seed pods was 2.9- to 3.8-fold higher than non-treated seeds. The extruded pellets have great potential for hydroponics since seeds can be placed directly into the growing support for gemination and growth. The major limitation of solid matrix priming is that after seeds are primed, the solid matrix material needs to be mechanically separated without harming the seeds.[57] This can be avoided if the seeds could be efficiently planted with the solid matrix priming medium. Furthermore, seeding efforts may be improved if the matrix priming material enhanced seed germination and seedling growth, or even providing nutrients for further growth. Nano-priming involves nanoparticles during priming to increase the germination percentage, seedling growth and seedling vigour. A recent study used turmeric oil nano-emulsions and silver nanoparticles (AgNPs) as nano-priming agents for diploid and triploid watermelon seeds.[60] The authors found that AgNPs was internalized, which was confirmed by transmission electron microscopy (TEM) and the seedling emergence rate at 14 days after sowing was significantly higher than for the control sample. Soluble sugar contents (glucose and fructose) were enhanced during germination in the AgNP-treated seeds at 96 h. The author also obtained a higher yield (more than 30%) than for the control. The authors attributed the enhancements to the accumulation of AgNPs in the seeds, which might activate the metabolic events and enhance the chlorophyll content that are vital for seed germination and seedling growth. The study implies that seed priming with AgNPs can enhance seed germination, growth, and yield while maintaining fruit quality through an eco-friendly and sustainable nanotechnological approach. Bio-priming is a sustainable and ecological technique to avoid the use of chemicals. In this method, various bio-control agents are used as a layer over the seed surface as a protective coat, which is safe for the environment and human health. Generally, fungal antagonists, e.g., *Trichoderma viridae* and *Trichoderma harzianum*, are used in bio-priming.

2.1.2. Seed Coating

Seed coating is the covering of seeds with external materials to modify the physical properties of the seeds with the aim of improving handling, protection, germination enhancement, and plant establishment.[47, 61-63] Seed coating materials can be grouped as active components, liquid, binder and solid particulates. Active materials can be categorized by their composition and their origin and they can be synthetic chemicals, natural products or derivatives from natural products, biological agents and minerals mined from the earth. The functions of these active ingredients include biostimulant, plant nutrient, abiotic stress relievers, plant protectant (for controlling pathogens and pests at the time of sowing, e.g., fungal and/or bacterial microorganisms), or as inoculants for nitrogen supply (**Figure 4**).[62] Liquid materials contain solvent, mostly water, colorant, adjuvant and binder. Solid particulates contain filler e.g., diatomaceous earth, limestone, vermiculite. Three major seed coating types have been developed: film coating – a thin layer of material is applied to the seed (less than 5–10% of the weight of the seed); encrusting – materials that increase the weight and volume of the seed are added but the shape of the original seed is still recognizable; and pelleting – materials are added to the seed to create an oval-spherical shape where the initial seed shape is indiscernible (see Figure 4).[51, 52] Further variations of seed coating have been developed and adapted in recent years for native plant seeds, such as seed agglomerates or conglomerates,[64, 65] in which multiple seeds are clustered together into a single delivery unit and extruded into pellets.[66] This process can be a combination of seed priming and seed coating.

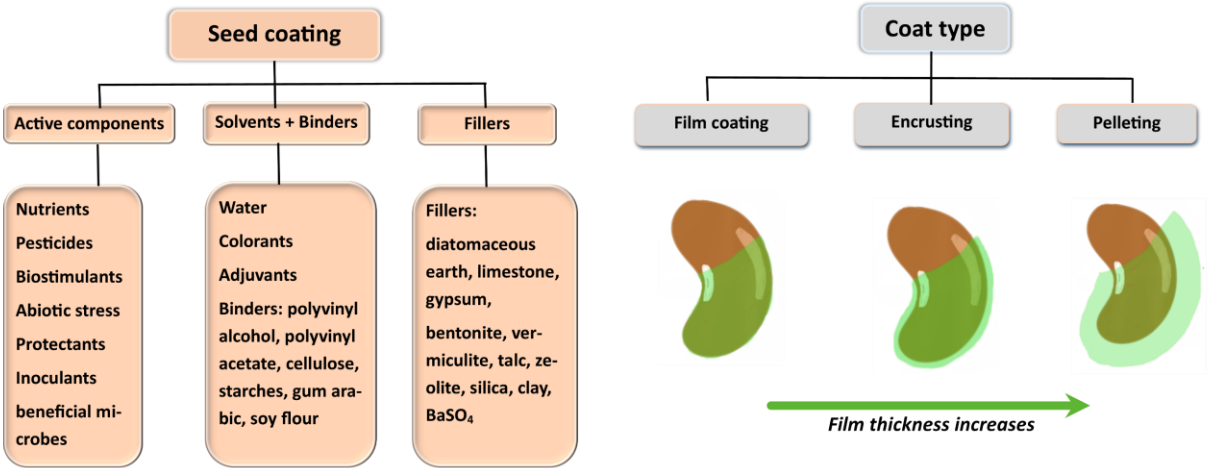

Figure 4. Seed coating recipe and type.

In the past decade, seed coating with nanoparticle is gaining some interest and various nanoparticles have been investigated.[62, 67, 68] In one study, the authors studied the uptake of Zn from seed coated with zinc oxide (ZnO) nanoparticles and it was found that seed coating with nanoscale ZnO did not exert any osmotic potential at the time of germination of the seed. Since there is no detrimental effect during germination, the total requirement of Zn of the crop can be loaded with the seed.[69] The fertilizer-based seed coating with ZnO protocol can be used by the seed producing agencies to produce customized seed for Zn deficient areas of the country.[69] Other seed enhancement technologies e.g. physical (magnetic, plasma, or radiation seed stimulation) and biological treatments have also attracted great attention. Among the physical methods, magnetic field and irradiation with microwaves or ionizing radiations are the most promising pre-sowing seed treatments, but these will not be discussed in this review which focuses on the materials science aspect. There is also research on microbial inoculants applied via seed coating and they are evaluated based on their effectiveness as a delivery system for microbial formulations and their effects on agricultural crops.[70] In a recent study, authors developed a biomaterial-based approach to engineer the microenvironment of seeds through the preservation and delivery of plant growth promoting rhizobacteria that can boost germination, are able to fix nitrogen and mitigate soil salinity.[71] They coated seeds with silk, trehalose and bacteria in a water mixture (**Figure 5**a). Silk coating can preserve the biological material and extend the shelf life of seeds. The nitrogen-fixing bacteria, namely rhizobacteria, provides a natural fertilizer to the plant crops. Trehalose is a kind of sugar and acts as nutrient to the mix. The coating combination provides sufficient mechanical robustness, adhesion and controllable degradation to the end material. Silk-coated seeds yielded plants that grew faster and stronger in the presence of saline soil (Figure 5b). Interestingly, the effectiveness of rhizobacteria coating in boosting seed germination and producing stronger seedlings was more evident in the high-salinity 8-ds/m soil (Figure 5c). The study opens the door to the application of advanced materials to precision agriculture and introduces innovative concepts to enhance food production while minimizing inputs and mitigating environmental impacts. The author later pointed out several issues with microbe seed coating.[72] For example, each seed can only contain a restricted amount of inoculant, which limits the number of bacteria for inoculation. The coating process may damage the natural coating of seeds and alter the water or oxygen absorption properties of the seed, thus affecting its germination capabilities. Therefore, seed treatments have to be optimized to avoid detrimental effects on the final product.

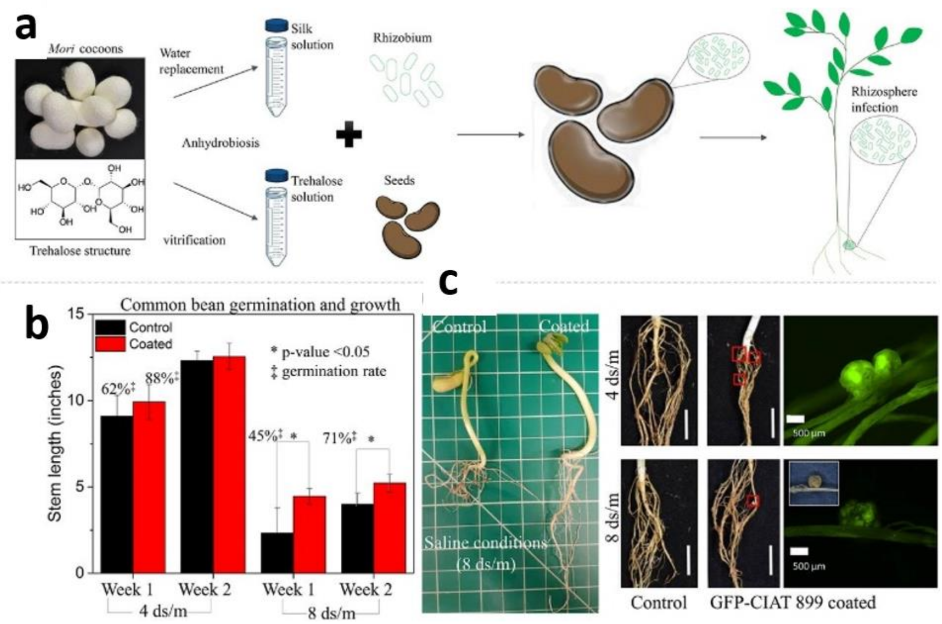

Figure 5. a) Schematic drawing of the method used to preserve and deliver CIAT 899 (a broad host-range rhizobial strain) to induce root infections through inoculation by seed coating of common beans. b) Germination rate and stem growth over a 2-week period. c) Digital photo and fluorescence microscope images of root nodulation.[71]

Although the above-mentioned seed enhancement strategies have been shown to improve the development of the plants in the various studies, some challenges related to seed for urban farming are still present. It remains to be seen whether it is possible to breed new plant seed suitable for both indoor and outdoor urban farming. Different plant species may need different recipes to ensure optimum growth. It would be very useful if a database can be created that contains the best recipes for individual plant species. It should also be possible to introduce phytoactive promoters into the seed coating to improve seed germination, seedling establishment, stress resistance, and potentially reduce the need for pesticide.[61] The above-mentioned seed coating technologies should be applied to native seeds and integrated with other aspects of seed enhancement, such as dormancy alleviation or seed priming treatments, to improve plant establishment for ecological restoration.

2.2 Growing Substrates and Additives

In traditional agriculture, soil is the default substrate for crop growth due to its easy availability and fertility. Soil is the most abundant and commonly used growth medium that can provide plants with a variety of nutrients to complete their life cycle. It is generally acknowledged that plants require a total of 17 essential elements (including carbon (C), hydrogen (H) and oxygen (O)).[73, 74] Among the rest of the 14 elements, nitrogen (N), phosphorus (P), sulfur (S), potassium (K), calcium (Ca), and magnesium (Mg) are needed at a larger amount and therefore called macronutrients or macroelements. The remaining micronutrients (or microelements) which are required in a relatively small quantity are iron (Fe), chlorine (Cl), manganese (Mn), boron (B), zinc (Zn), copper (Cu), nickel (Ni), and molybdenum (Mo).[75]

Land scarcity is a major limitation to the use of soil cultivation in urban areas, especially in the highly developed metropolises.[76-78] For populous cities, cultivation venues are greatly diversified and more integrated into the urban landscape with the emerging rooftop farming, vertical farming, indoor farming, and small-scale household farming. Admittedly some projects are still using traditional soil as the cultivation medium as it is most available, other considerations such as durability, availability of essential nutrients, and water management are more important factors to consider when selecting substrates in the urban cultivation environment. Urban soil contamination, which poses a health risk to gardeners and end consumers, is a growing concern but usually overlooked.[79, 80] A wide range of contaminants are found, namely, heavy metals (e.g., lead, cadmium, arsenic), organic chemicals (e.g., pesticides, PAHs, oil), trash (e.g., plastic, needles, glass) and many other pollutants.[80-83] On top of the lack of easy access to good quality soil in urban settings, soil as growth medium will not be able to offer to precise control on the environmental and growth considerations mentioned earlier. Soilless culture can be a solution where substrates other than soil are employed to adapt to different scenarios. Generally, soilless agriculture has the advantages of higher productivity, decrease in water and fertilizer usage, better growth control and less labor intensive.[84-86] Among the many growing methods, hydroponics is the most popular soilless culture which has a history of more than 70 years. In the recent years, hydroponics has evolved into variants like aquaponics and aeroponics. Thanks to its adaptability, hydroponics has contributed greatly to the food supply in arid or populous land-scarce urban areas.[87-89] Even though hydroponic culture is quite established (well elaborated in many reviews and books), it is less suitable some types of plants such as those with deep root systems, plants that growth to tall heights and also most vining plants. Alternative substrates or growing additives have been investigated to address the problems of soil cultivation and the limitations in hydroponics to meet the sustainable requirements in modern urban settings. Some of these alternative substrates will be discussed in this section.

2.2.1. Zeolites

Zeolites are naturally formed aluminosilicates in sedimentary rocks. Owing to its outstanding water retention ability, cation exchange capability (CEC) and “slow-release of adsorbed species” character, it is widely applied in agriculture as soil-conditioner, fertilizer-, pesticide-, insecticide-carrier, etc.[90-92] The first series of studies on the use natural zeolites as a growing medium for soilless culture (named zeoponics) was conducted by NASA in the 1990s. Higher wheat yield was achieved in the zeoponic system by adding nitrifying bacteria and dolomite, while in another study wheat seed production from zeolites only slightly fell short of that from hydroponics.[93] In a follow-up test, it is found that zeolites can produce greater crop yield in each successive growing cycle.[94] Despite NASA successfully demonstrated the use of zeolites as growth medium, this did not take-off in the agriculture scene. Instead, the focus since then was on the zeolites as a soil additive only rather than in a full zeoponic system.

The original concept in NASA proposal where by all the plant growth nutrients are supplied by the growth medium for several growth seasons with only the addition of water is desirable but yet to be fully realized. [95] It is potentially inhibited by vast variations in the properties of different natural zeolites and the poor adsorption of negative ions into zeolites, despite the latter can be addressed with the use of surfactants modified zeolites which can be used as a slow-release fertilizer to supply nitrate, phosphate, and sulfate.[96-98] It has also been reported that phosphate may attach to crystal defects with exposed hydrated oxides, but the release of such charged phosphate was inadequate after one month of growing of chrysanthemum.[99]

Migrating zeolites from space to urban agriculture is almost seamless, since the two environments shared many similarities – limited space, high yield requirement, autonomous growth, and the need for recycling. Our research collaboration between Nanyang Technological University (NTU) and Panasonic Factory Solutions Asia Pacific Singapore was supported under the Singapore Food Agency Agriculture Productivity Fund to utilizes nutrient loaded zeolites as an alternative substrate to cultivate leafy vegetables for local supply. The selection of zeolites is stringent and based on chemical composition, surface area and CEC. The understanding of zeolite capacity for fertilizer uptake and release is of paramount importance. The studies will help establish an in-depth understanding of the intrinsic properties of zeolites. While zeolites are responsible to capture cation nutrients, metal nanoparticles and easily protonated polymers are decorated onto zeolites for the adsorption of anions. Early-stage plant growing tests revealed promising results on vegetable yield (**Figure 6**), supporting the choice of zeolites as suitable media for a few successive growth cycles. Yet little is known regarding plant-specific or zeolite-specific nutrient uptake, and the relationships of these properties with nutrient solution refill; it is also unknown that how sterilization will affect future plant growth. All in all, several key aspects remain to be solved: the optimal fertilizer concentration, the pre-treatment on zeolites, the recycling of the substrates and the replenishment of fertilizer.

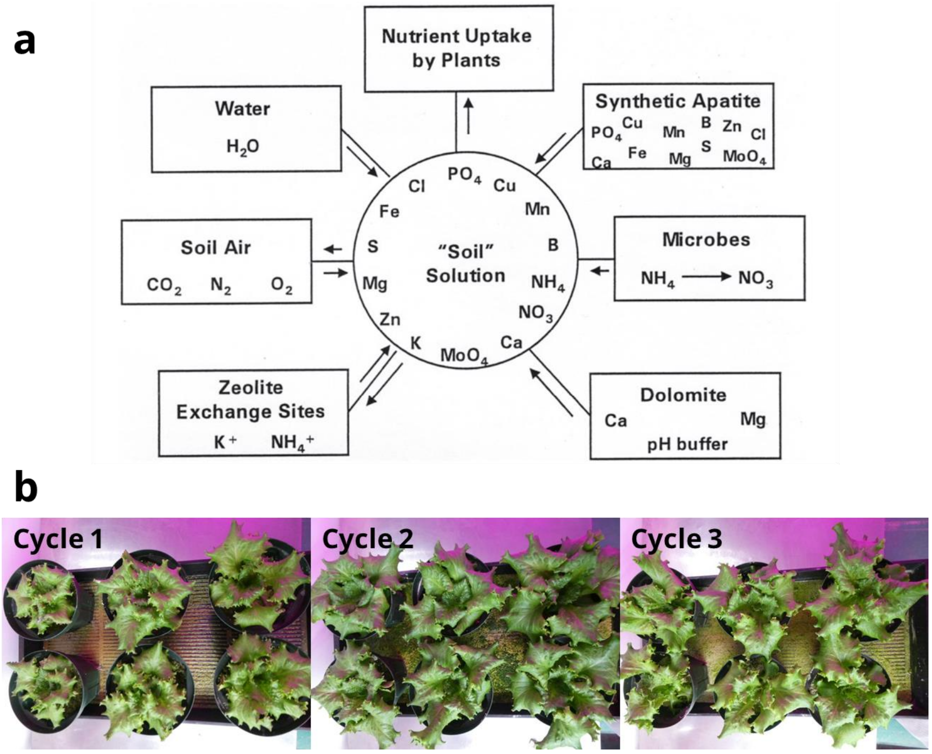

Figure 6. a) Dynamic equilibria of growing elements for NASA's zeoponic plant growth system.[93] b) Images of green lettuce cultivated in zeolites for three continuous growing cycles. Photo: Panasonic Factory Solutions Asia Pacific (PFSAP), Singapore. a) Reproduced with permission.[93] Copyright 1999, Springer Nature.

Our system adopts the NASA original concept of only adding water after the initial nutrient loading and the growth substrate is recycled, and thus saves costs and demands less human intervention which are especially favorable in urban farming. In the future, vegetables planted in zeolites can be intensively grown on racks under artificial illumination. The all-element-controlled indoor vertical zeoponic integration fits well into Singapore's "30-by-30" food production goal as a more sustainable and resilient urban ecosystem.

2.2.2. Superabsorbent Hydrogel and Biopolymers

Superabsorbent hydrogels (SAH) are a class of polymers with significant number of hydrophilic groups (carboxyl groups, amino groups, hydroxyl groups, etc.) present along the polymer chain to confer high water absorbance and retention.[100] SAH can be synthesised from natural (e.g., cellulose, starch, chitosan, alginate)[101-108] or synthetic (e.g., polyacrylic acid, polyacrylamide)[108-110] sources; by combining both sources, as well as controlling the degree of crosslinking, will allow the tuning of the water absorption and degradability properties. As SAH is more absorbent than normal hydrogels, they further improve the water retention capability of soil and reduces evaporation loss.[111] It is often used to relief plant dehydration post transplanting and applied in plantations with trees and larger-sized food crops where effects of irrigation and rainfall are either less predictable or non-uniform.

In urban farming, optimum utilization of land, labour, water and energy resources are paramount to its success in food production. There is a need to enhance water efficiency (to reduce cost and to conserve precious water resources) and improve production efficiency (lower manpower requirement). SAH is found to be particularly useful during crop growth in addressing these two points. Proper usage of SAH alleviates drought stress to a large extent, and its effectiveness as water management tool will be explored further in Section 2.4.1. One good example is roof-top planting, where the complex irrigation facility can potentially be replaced with the application of SAH. However, most commercially available SAH require pre-soaking in water to form large solid clumps which are then applied via soil churn, making them suitable only for new plantings. If the application was not done properly, water superabsorbance property may introduce unwanted effects including localized sogginess, algae growth, and root rot, threatening plant survivability instead.[112]

The focus on developing SAH is now turning from “bringing water as close to plant roots as possible” to ensuring an even distribution of sufficient soil moisture to keep plants well-hydrated, as plants innate hydrotropism drives roots to sense and search for moisture. Lam’s team successfully synthesized RetenSol™ nanogel formulations comprising nanosized gel particles of varying degradation rates that are capable of high water absorbency.[113, 114] By controlling the dry and swollen particle sizes, the nanogel particles remain small enough when swelled to allow direct mixing with water in irrigation systems without causing clogging, thereby improving dispersion homogeneity in soils. A recent version of RetenSol™ extended its application to soilless substrates comprising zeolites, which can find potential utility in urban farms.[115] Optimization of highly absorbent nanomaterials will continue to allow economical application and increase operational flexibility without risking the potential issues arises from waterlogged soil. There is a strong need to develop new generation SAH that addresses durability and sustainability while other advantages remain.

Figure 7. Results of 1-week drought tests on 3 plant species: a) *Amaranthus tricolor*, b) *Alternanthera brasiliana*, c) *Pentas lanceolata* with water (top / left) and water + RetenSol™ formulation (bottom / right) applied on Day 0. The survivability of all 3 species under drought stress is significantly improved when soils were given our formulation prior to the drought.

Polymers derived from natural sources (named as biopolymers) are usually inexpensive, abundant, and biocompatible. As mentioned earlier, these polymers can be used as the starting material for making superabsorbent polymer gels for water management in farming. Cellulose-based SAH, for instance, represent an emerging cluster of products made from natural biomass resources that potentially can meet the requirements of different fields other than agriculture.[116] Apart from this, there are many other applications of cellulose, chitosan, alginate, plant gums, lignin, and their derivatives in agriculture.[117-123] An interesting area of research is the mixing of biopolymers with other growth media as the biopolymer additives has shown to protect plants from disease, fungus or pathogen and improving yield.[119, 124-126] Biopolymers can also function as encapsulant of nutrient or pesticides and this can allow for sustained nutrient or pesticides release and will be explored in Section 2.3.[10, 127-130]

2.2.3. Recycled Materials

Globally, waste generation in cities is causing a major issue to most countries and this has yet to be tackled in a satisfactory manner. Among the 3-R (Reduce, Reuse, Recycle) guidelines, to recycle is the most direct way to deal with the existing waste. Connecting the booming municipal waste with the growing need for urban growth medium would help to change refuse into a worthful means of production.

Such strategy has been reflected in various research projects targeting different types of waste materials, in which compost-based growth substrate has the most widespread interest. Traditionally waste utilization in agriculture is confined to disposed vegetables and food debris, composting sources have now expanded to wood waste (e.g., pine bark),[131] post-processing waste (e.g., sugarcane bagasse, fresh orange waste),[132-135] and even municipal solid waste (MSW).[136] The addition of compost substrate boosts plant cultivation by supplying extra nutrients, which is proved by elemental analysis of compost and later indicated by the increased fresh weight, dry weight, leafy area, and other quantitative factors of plants.[132, 137, 138] Some results also show that heavy metals in the studied MSW compost are mostly below the allowed limits in different standards;[136, 139] but the possibility of assimilation by plant and the effect of accumulation cannot be ignored and should be carefully considered in the long term.[140, 141]

In the pursuit for sustainable cities, green roof in cities is acknowledged as a sustainable tactic to mitigate urban heat island effect and this can bring many other social, environmental and economic advantages.[142] For the selection of growth medium on the green rooftop, it is certainly a good option to select “green” recycled construction waste material especially if the overall weight is reduced. Small scale experiments conducted in the lab confirmed the adequacy of recycled aggregates in supporting plant growth on the rooftop.[143] Smaller bricks, in a quantitative assessment, were found to own a higher water holding capacity than larger bricks and barks. Added benefits on plants, such as healthier nutrient status, better root growth and lower root-shoot ratio, were observed when small-grain aggregates were applied together with compost and water retention gel.[144] Consistently, crushed demolition waste (bricks, porcelain, and foamed glass) is suggested for the installation of green roofs (**Figure 8**a), based on two separate experiments.[145, 146] It is worth mentioning that many reported green roofs adopted a combination of substrates containing construction waste, which stresses the importance of tailoring various growth substrates to achieve an optimal growing performance.

Recycled plastics (the caps and bottoms of PET bottles, Figure 8b and c) can also function as well as the commercial green roof drainage layer in a preliminary study exploring the variety of useable waste materials.[147] There is a recent attempt to recycle polyvinyl chloride (PVC) plastics into novel plant growth substrate by coupling surface silanized PVC with superabsorbent resin and compress it into foam (Figure 8d).[148] The low-temperature process avoided toxic chlorinated side products, while the composite maintain a higher level of mechanical properties and comparable water absorbing and retention properties at a 50% lower cost as compared to commercial products on market. It can be expected that in the near future, various forms of recycled materials, including but not limited to construction waste, plastics and other municipal solid waste, would emerge in an effort to build a more sustainable urban agriculture. However, long-term close monitoring of the potential leaching of toxic substances from all recycled materials should be examined before and after their use as growth substrates.

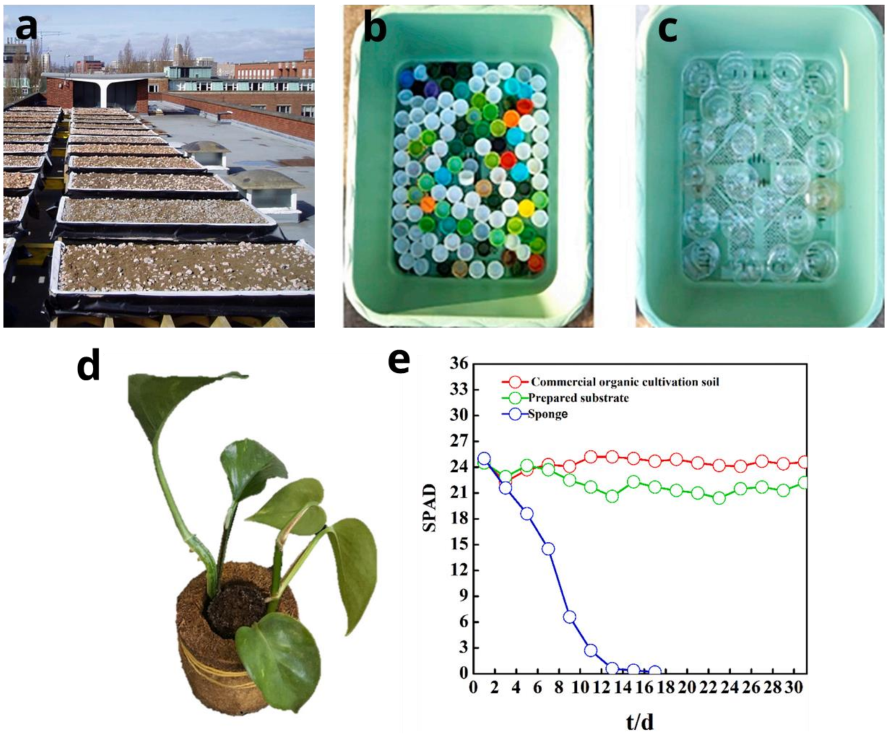

Figure 8. a) Recycled aggregate as a growth substrate for vegetation development on rooftop.[145] b) recycled bottle caps c) recycled bottom parts of plastic bottles used as a green roof substrate.[149] d) *Epipremnum aureum* kept in the substrate made from waste PVC and superabsorbent resin. d) growing condition of the plant cultivated in three different greening substrates indicated by SPAD values.[148] a) Adapted with permission.[145] Copyright 2015, Elsevier. b,c) Adapted with permission.[149] Copyright 2020, Elsevier. d,e) Adapted with permission.[148] Copyright 2021, Elsevier.

2.3. Nutrient Delivery

One advantage of hydro-, aqua- or aeroponics is that the nutrient delivery to plant is straightforward and more efficient than soil-based systems. Plants obtained the needed nutrients via the roots immersed in growth media or exposed to nutrient-ladened air. An automated nutrient delivery system can inject fertilizer and pesticide into an irrigation line. Meanwhile the electrical conductivity, pH, and temperature in water can be controlled using sensors to provide feedback and the level can then be either automatically or manually adjusted. It allows the farmer to deliver a precise amount of nutrients, based on the crop type and growth medium, thus saving valuable time and reducing labour costs, waste and impact to the environment.

For the other forms of urban farming, especially soil-based farming such as some indoor farming, rooftop farming or small plots farming, the nutrient delivery is not as efficient. Most fertilizers can potentially leach into the ground water, run off into our wastewater system or volatilize into the atmosphere. Thus, giving just the right amount of nutrients critical for the plant growth is important as this will reduce the cost and impact to our urban ecosystems. Nanotechnology has the potential to be able to precisely control the amount of nutrients delivered. The use of nanostructured materials such as nanoparticles, nanohydrogels, and nanoemulsions for the delivery of nutrients, pesticides and bioactive compounds (genes) will allow for controlled and sustained delivery of these cargoes such that their negative impact on the environment will be limited. Nanomaterials based on inorganic, organic and composite materials have been tested on various plants to assess their potential impact on plant growth, development and productivity.[150] Kottegoda *et al.* developed an advanced nitrogen nanofertilizer using urea-coated hydroxyapatite nanoparticles for targeted delivery and slow release of nitrogen (**Figure 9**).[151] The nanohybrid of urea-modified hydroxyapatite, synthesized with nitrogen weight of 40%, releases nitrogen twelve times slower than conventional urea due to the moderately strong bond between the amine group of urea and carbonyl group of hydroxyapatites. Field trials with rice showed that slow-release properties of the nanohybrids resulted in better yield at 50% of urea concentration.[152]

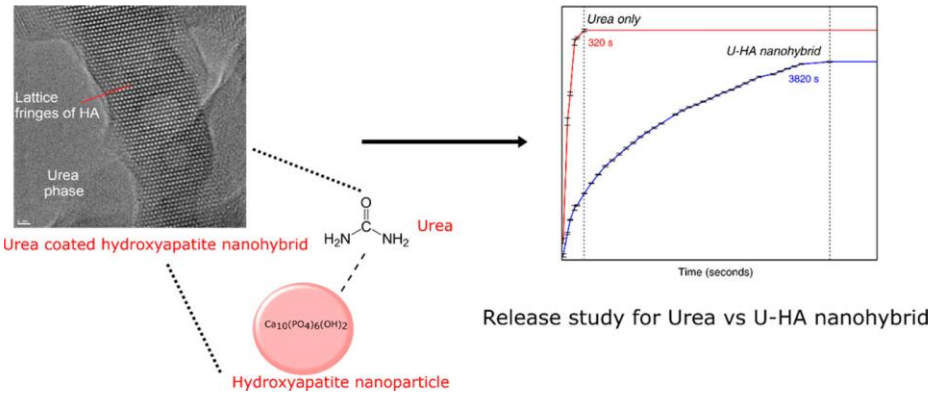

Figure 9. HRTEM image and schematic showing urea-modified hydroxyapatite nanohybrid as fertilizer and its release behaviour with and without hydroxyapatite.[151]

Currently, foliar application of micronutrients on plants over an extended time is challenging and often not possible due to insufficient rain fastness. There have been some strategies to overcome this issue. One study reported a novel foliar fertilizer delivery system based on functional pH-responsive biohybrid poly(allylamine) microgels that have orthogonal functionality as carriers of micronutrients and employed peptides (termed anchor peptides) as the foliar adhesion promoters.[153] The anchor peptides bind onto hydrophobic surfaces and the waxy “islands” of plant leaves. The authors found that microgels can be loaded with tuneable amounts of Fe^{3+} ions and show strong binding to leaf surfaces. The application of Fe^{3+}-loaded microgels onto iron-deficient cucumber plants showed significant “re-greening” and an increase in the chlorophyll content in leaves confirming an efficient delivery of metal ions. The biocompatible and non-phytotoxic nature of poly(allylamine) microgels enables their general application as a novel delivery system for plants. Similarly, another study demonstrated a nanoscale platform that targets and delivers nanomaterials with biochemicals to plant photosynthetic organelles (chloroplasts) using a guiding peptide recognition motif.[44] The author found that the delivery of methyl viologen and ascorbic acid by quantum dot (QD) allows tuneable changes in chloroplast redox status by inducing or reducing superoxide anion production in this organelle with high specificity (see **Figure 10**a). The chloroplast targeting peptide, designed from Rubisco small subunit 1 A (RbcS) with a 14-amino acid, was used to functionalize fluorescent cadmium telluride QD for targeting chloroplasts in intact leaves of plants *in vivo* (Figure 10b-d). The authors found that peptide biorecognition provides high delivery efficiency and specificity of inorganic quantum dot with chemical cargoes to chloroplasts in plant cells *in vivo* (74.6 ± 10.8%, two times higher than the control) and hence there can be more specific tuneable changes of chloroplast redox function than chemicals alone. The concept could be extended to other types of nanomaterials for applications including genetic cargo delivery, targeted delivery of sensors, nutrients or pesticides to specific plant tissues or subcellular compartments.

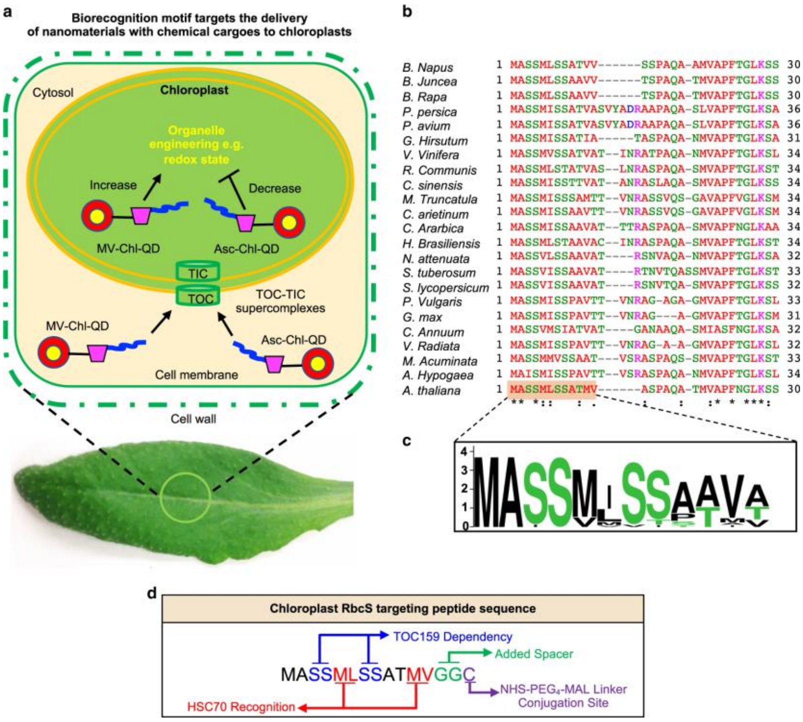

Figure 10. a) Schematic drawing of quantum dots coated with a chloroplast guiding peptide (in blue) and a molecular basket. b) Chloroplast transit peptide sequences (partial) from several plants. c) Frequency logo plot of targeting peptide. d) Designed guiding peptide.[44] Copyright 2020, Springer Nature.

Despite their tremendous advantages, the employment of nanomaterials as a delivery carrier for nutrients, pesticides and bioactive compounds also comes with some risks relating to their potential delivery to undesirable locations and their release on non-targeted organisms, including plants and plant-associated soil microbes, or the timing of the release.[154] Depending on the type of nanomaterials, there can also be risks associated with the dose applied. Therefore, before any large-scale adoption of nanomaterials in urban farming, research must be conducted to assess the agro-ecological impacts, including the activity of the different nanomaterials on specific plants, dose studies and their biotoxicity.

2.4. Environmental Management

As the growth of plants is highly influenced by their surroundings, success in agriculture development hinges upon efficient mitigation of unpredictable environmental factors such as drought, floods, heat and freeze. This has limited success in outdoor farming. Urban farming, especially indoor farming, provides the unique opportunity for controlling the environment.

For large-scale commercial vegetable cultivation in urban cities to be viable, environmental control is in fact necessary for stable year-round production.[11, 155] Precise control of environmental factors can also help to revisit and solve some important and sophisticated biological problems.[156] From greenhouses to plant growth chambers and phytotrons, with increasing agriculture cultivation knowledge and more advanced technology available, control of the environment can be achieved which has been impossible for outdoor cultivation. [11, 155, 157] A typical controlled environment allows the control of temperature, humidity, illumination and carbon dioxide (CO_2) concentration.[155] A combination and optimization of those factors can boost the production yield and although improving the quality of the produce is a challenge, with improved technology and better integration of sensors, this will become a reality.[11, 155, 158, 159] In this section, the application of novel functional materials to control the micro-environment for urban farming will be discussed.

2.4.1. Water Management

Water management in farming is essentially the mitigation of drought in the root zone and modulation of the intense transpiration on leaves. One possible solution to avoid drought in the root zone is the replacement of soil with superabsorbent hydrogel (as discussed in detail in Section 2.2.2.) to greatly improve the water retention capability of the growing substrate. The application of superabsorbent polymers has witnessed substantial yield increase in arid areas in Iran and China.[160, 161] Transpiration can be regulated using a controlled growing environment (such as in an indoor farming), but is still not possible for open or semi-open urban farms.

Irrigating urban farms using municipal water resources is both energy intensive and very costly. The situation is even worse when it comes to cities that rely on desalinated or underground water, hence harvesting water from atmospheric humidity is an attractive solution. A hygroscopic Cu-complex (copper-ethanolamine) has been synthesized and reported to adsorb water at a superior capacity of 3.0 g g^{-1} and produce water at a rate of 2.24 g g^{-1} h^{-1}.[162] It was further integrated into solar panels giving rise to a SmartFarm device (**Figure 11**a). The Cu-complex can harvest atmospheric water at nighttime and release the stored water to plants when exposed to sunlight during the day. Baby Kangkong (*Ipomoea aquatica*, a popular local vegetable) was successfully cultivated in the SmartFarm device during a 10-day test. Similarly, a super moisture absorbent gel (SMAG, isopropylacrylamide-based) was developed to realize atmospheric irrigation, which is tested to sustain plant growth for at least 14 days without additional watering in a closed system (Figure 11b).[163] These prototypes are showing great promise for future automated growing chambers where they will be free of any human intervention on irrigation.

Another example of an autonomous atmospheric water seeping material is based on a metal-organic framework (MOFs) and N-isopropylacrylamide aerogel mixture.[164] The addition of MOFs make it distinct from the previous Cu complex and SMAG in that its water collection is continuous at a record rate of $6.04\ \mathrm{g\ g^{-1}}$ (95% efficiency) and reduces its dependence on solar-assisted adsorption-desorption cycles (Figure 11c). This suggests a wider range of applications ranging from growth chambers to open-space self-irrigation farming, which can translate to simpler infrastructure needs as the need for solar panels or a chamber building are circumvented.

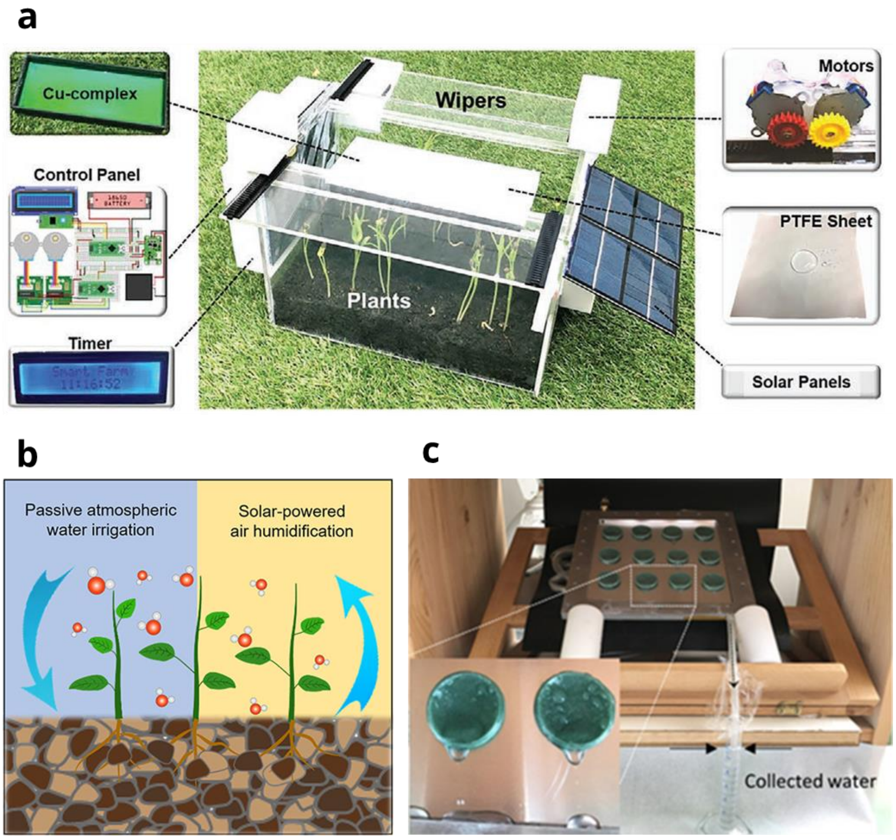

Figure 11. a) Photograph of the SmartFarm prototype showing its components.[162] b) Schematic of the atmospheric water adsorption and release cycle on super moisture absorbent gels.[163] c) Water drops from the proof-of-concept prototype for atmospheric water harvesting.[164] a) Adapted with permission.[162] Copyright 2020, John Wiley and Sons. b)

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2.4.2 Light management

Light plays a crucial role in every stage of plant development, from seed germination to morphogenesis and flowering.[165, 166] Photoperiodic management using blackout curtains and energy-saving LED lighting to control light availability to plants is now a standard way to regulate the growth of indoor plants based on their types (short-day, long-day, and day-neutral plants).[14, 167] The effect of light sources is reported to optimize the growth and development of plants (see elsewhere).[168-172] One major topic relating to the availability or lack of light is the regulation of the shade avoidance response in plants. This is plants' response to the change of neighboring light signals and is detrimental to plant health and crop yield. It can be addressed through multiple pathways: controlling light quality and quantity, inducing mutations and phenotypic screening, and hormonal regulation.[173-176] Very recently, early screening of the shade avoidance response can be realized by detecting metabolite changes in leaf blade and petiole *in vivo* using Raman spectroscopy.[177]

Controlling the ambient light exposure to plants is not sufficient to promote the intrinsic photosynthetic activities. The development of nanotechnology has opened new possibilities to alter plants' response to light and to enhance light absorption efficiency. Although many common nanoparticles have been studied,[12, 13] for example, TiO_2 is found to increase light absorption in the red and blue regions,[178] more innovative luminescent nanophosphors have been developed and used for improving photosynthesis.[179, 180] Down-conversion phosphors with single or dual spectrum emission overlapping with the main absorption region of plant pigments are potential candidates for indoor plant growth lighting.[181-183] In contrast, up-conversion materials have received increasing attention for plants, not only for cell imaging but also for light harvesting. A prior experiment on *in vitro* coupling of porous $NaYF_4$ with chlorophyll verified that red light converted from near infrared by the up-conversion material can be transferred to the biomolecules.[184] In another study, citric acid coated $NaYF_4$ (Yb^{3+}, Er^{3+}, and Tm^{3+} co-doped) nanocrystals (**Figure 12**a) were fed to Mung beans.[185] Interestingly, $NaYF_4$ applied at a low concentration (10 μg/mL) accelerated the growth of bean sprouts (Figure 12b). Under laser scanning, up-conversion nanoparticles were seen in roots, stems and leaves, implying that it can be successfully delivered via the vascular system without decomposition. A similar study combining carbon dots (CDs) with $NaYF_4$:Yb,Er found that this combination helps in the photosynthesis of Mung beans due to enhanced up-conversion red emission.[186] However, the toxicity of up-conversion nanoparticles remains a controversial subject and its effect on plants is highly dependent on the species of plants and the type of up-conversion materials combination.[181-183, 185, 187, 188] Future research on up-conversion materials should take into account their biocompatibility and biosafety.

The interaction between light and temperature can help to regulate plant growth.[189-192] For example, an investigation into the freezing tolerance in plants discovered that several cold-related genes are influenced by light.[193] Light as an energy input can also drive the phytochromes whose activities are usually temperature sensitive. A plant's reaction to light is also linked to transpiration and temperature adjustment. At the molecular level, the phytochrome B (phyB) receptor senses both light and temperature. Downstream signalling components (phytochrome interacting factor 4, constitutive photomorphogenic 1, and elongated hypocotyl 5) also depend on the changing light and temperature conditions.[190] Although it is not within the scope of this review, it has to be mentioned that the effects of light and temperature on plants should not be separated due to their extensive convergence in signalling. Consequently, light and temperature management on plants should be considered together in real-life scenarios.

2.4.3. Temperature management

Global climate change exacerbated by greenhouse emissions is expected to cause a rise in global temperature by 4 °C before 2100.[194] This will be detrimental to agricultural production. There is existing evidence to link the declining corn and soybean yields in China to climate change.[195] Generally, plant developmental response to climate change takes time to evolve.[196] In order to ensure high agriculture productivity with the changes in climate, it is important to be able to regulate the environment and this can be done in an indoor farm. Controlled lighting using LEDs offers an opportunity for artificial light management in an indoor setting and novel materials that is being developed for use in energy conversion/storage and cooling coatings have opened up many possibilities in this area.[14, 197, 198]

The cost of heating, ventilation and air-conditioning (HVAC) in greenhouse and other indoor growing facilities accounts for 20-50% of overall building energy consumption.[199, 200] Success in attempts to curb energy consumption in growing crops indoors hinges on the ability to control the temperature in the farm. Technically, many green facilities have been engineered to provide farms with more sustainable heat and electricity, and this includes the use of photovoltaic (PV) modules, thermal collectors, geothermal units and wind power.[15] Novel materials have been developed to curb energy consumption in some of these indoor farms and one such opportunity is the use of coatings and phase change materials on walls, windows and glass roofs. For building with windows, the inside temperature is closely related to the transmitted light as the heat presence in an internal space is contributed by infrared light entering through the windows. A smart window that reflects infrared light on hot days and allows infrared light to enter on colder days while maintaining its transparency in both conditions can be a solution to greenhouses and other glass-roofed growth rooms. A range of electrochromic and thermochromic materials has been considered, including cholesteric liquid crystalline, vanadium dioxide, tungsten oxide, ionic liquids, perovskites, etc.[201-204] A layer of nano-silicone based coating on glass or acrylic surfaces is another innovation by NTU.[205] Such coatings can block around 90 % of the heat while allowing light to shine in so that the growth of plants is not compromised (Figure 12c). Based on an on-site test in a hydroponic farm in Singapore, the application of such solar shielding coating can result in an increase in average leaf width and weight increase by 7% and 30% respectively, despite the light intensity being cut down by nearly 70%.

In cold countries, thermal energy storage (TES) using phase change materials (PCM) with a high specific heat capacity provides a possible solution to keep the temperature high. Beyhan *et al.* used a PCM mixture of oleic acid and decanoic acid in containers surrounding the substrate to keep it warm in soilless agriculture greenhouses.[206] The temperature of the substrate in the PCM container during the night was measured to be 1-2 °C higher than the control, demonstrating that PCM may be suitable to be used for temperature control. A more detailed numerical model was performed to help maintain the temperature in plastic greenhouses above 10 °C for an all-day use strategy during cold winter days.[207] There is no direct contact between the PCM installed in walls or surrounding substrates and the plants, which is a great advantage in farming to avoid heat stress and chemical contamination.

A further combination of light blocking and energy storage leads to the development of a high thermal energy storage thermo-responsive smart window (HTEST smart window, Figure 12d) filled with a hydrogel-derived liquid (based on N-isopropylacrylamide).[208] It is reported that it shows excellent thermo-responsive optical properties and outstanding specific heat capacity, retaining 90% of the luminous transmittance. The HTEST smart window is perfect for conserving energy – compared with normal glass used in Singapore, there is a reduction of 44.6% HVAC in energy consumption indicated by simulations.

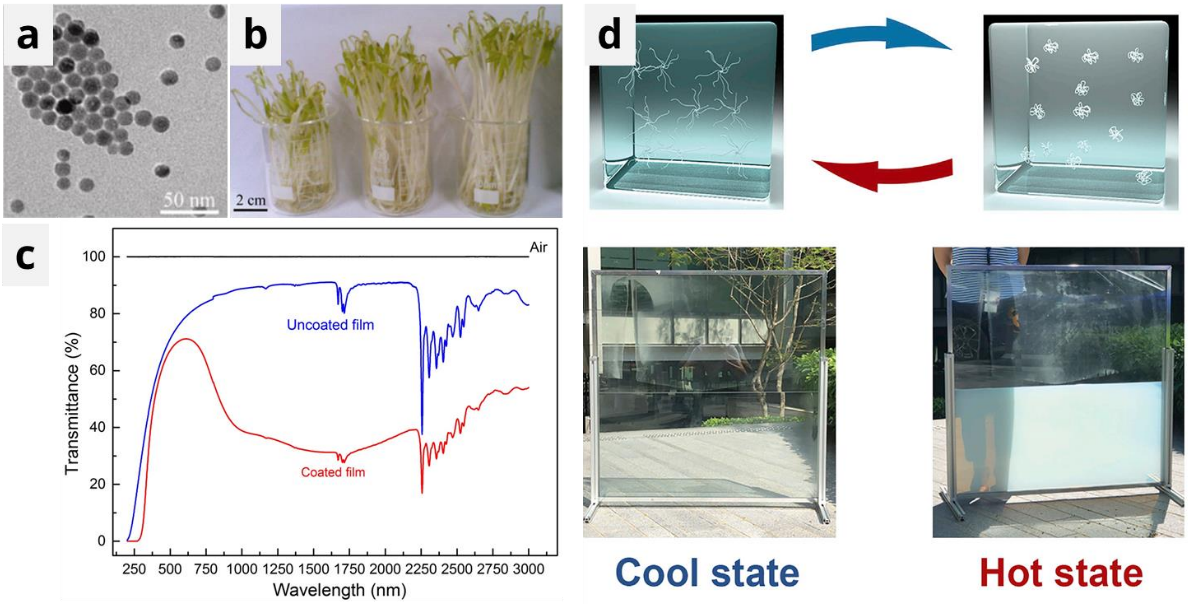

Figure 12. a) TEM image of the $NaYF_4$ up-conversion nanoparticles and b) its application to Mung beans at a concentration of 100 μg/mL (left) and 10 μg/mL (right), the middle beaker was cultivated with water only.[185] c) UV-Vis-NIR spectra of plastic films with or without the thermal insulation coating. d) microstructure and photo of a 1 m^2 window (half-filled with hydrogel) tested at different times of a day, showing the switch between cool and hot states.[208] a,b) Adapted with permission.[185] Copyright 2012, Springer Nature. d) Adapted with permission.[208] Copyright 2020, Elsevier.

Plants themselves regulate leaf surface temperature through transpiration.[209] Plants growing in hot and dry areas can effectively avoid overheating by transpiration rate adjustment and some intrinsic physical traits of the leaves. Application of a reflective kaolin coating insulates leaves from solar radiation and in some studies can reduce the leaf temperature as well as transpiration rate.[210, 211] Unfortunately very little conclusive evidence can be drawn on the effect of kaolin due to inconsistencies in the experimental design and plant species probably due to its influence on photosynthesis.[212, 213] Some coating materials based on nanoparticles (such as TiO_2, ZnO and SiO_2) that are applied on leaves for the purpose of nutrient or drug delivery may have a potential impact on plants transpiration and photosynthesis.

In short, though climatic control in an indoor farm may require a huge energy input, this energy requirement can be reduced by using innovative materials solutions such as smart windows and cooling coatings. Furthermore, electricity generation based on novel functional materials or devices – perovskite solar cells,[214-216] triboelectric nanogenerators,[217-219] thermoelectric generators[220-222] – can become an important energy source for sensors (Section 2.6), pumps, LEDs, etc. in future sustainable and smart farms.

Agri-environmental control is fast becoming an important development area to ensure the success of urban farming. However, it is very unlikely that there is a “one-size-fits-all” solution addressing all factors (light, temperature, water, air, substrate, etc.) for all plant species and growth conditions, especially when the understanding of microenvironment control is still lacking. In addition, we need to consider how to adapt urban farms (or even all farms) to the climate changes which are very much a reality that people are coming to terms within this century.

2.5. Pest/Disease Control and Pesticide Delivery

Compared to conventional farming, urban farming has less issues relating to pests and disease, but it still requires good pest and disease control as in most cases the farm consists of a large amount of horticultural fresh produce in an enclosed space,[223] intensive production and high humidity which create an excellent environment for the proliferation of pathogens and pests. For example, arthropod pests or plant diseases can be introduced into protected horticulture systems through accidental contamination due to human activity or incoming materials such as seeds and/or substrates in combination with inadequate phytosanitation protocols and/or poorly maintained glasshouse and vertical farming structures.[224] Disease and pests thrive in this environment, and can cause damage through herbivory and vector plant pathogens. One can use beneficial organisms to control unwanted pests, including certain types of bacteria and fungi, to control spider mites and other invaders by crowding them out, eating them or releasing compounds toxic to the pest. In most cases, due to economic considerations, the usage of pesticide is still necessary in such farm settings. The most frequently applied pesticides are insecticides to kill insects, herbicides to kill weeds, rodenticides to kill rodents, and fungicides to control fungi, mould, and mildew. Currently, the way that these pesticides are delivered is ineffective and hence farmers resort to frequent and higher dose application schemes, resulting in higher economic and environmental costs. Novel pesticides should have a selective mode of action and a unique chemical structure to target only undesirable organisms, but not be toxic against non-targeted organisms such as humans and beneficial organisms. New trends in global pesticide development are shifting from chemical pesticides to biological pesticides, gene modification crops, seeds, RNAi pesticides, and abiotic stress control agents. Biopesticides derived from natural materials as animals, plants, bacteria, and certain minerals and have attractive properties such as inherently reduced toxicity, target-oriented, short residue periods, and are thus highly effective.[225, 226]

On top of the development of pesticides, the creation of new design concepts that make use of materials in pesticide delivery is also contributing towards making farming more sustainable, which is important in urban settings as the impact to human can be felt acutely. Nanoencapsulation of pesticides can greatly reduce the amount of pesticides used, by solubilizing them and by providing controlled release of these chemicals at the target site.[227] Pesticides which can be hydrophobic and hydrophilic in nature can be encapsulated using organic or inorganic materials and thereby impart high surface area, exhibit tenable colloid properties and potentially chemically functionalizable surfaces.[9] Nature-derived polymers, e.g., cyclodextrin, chitosan, cellulose, are commonly used as a matrix or carrier with molecules that have low solubility in aqueous media. Zhao *et al.* developed a nano-emulsified pesticide displaying high stability over time (~ 3 months) and stronger absorption on negatively-charged surfaces, which are desirable characteristics for spray-based foliar applications of pesticides in crops.[228] Specific pesticide systems responding to specific stimuli are desirable to allow more precise control over the release dynamics. The most common stimuli triggering pesticide release in botanical applications relates to the presence of enzymes, changes in temperature, light, humidity, pH and ionic strength, as well as variations in biomarker levels and excretion of natural exudates from harmful organisms. Carriers that possess a multiple, higher degree of sensitivity are often beneficial for the development of delivery systems with fine-tuned release profiles.[229] For example, a novel pH and redox dual-responsive cellulose-based nanogel was prepared for the controlled release of agrochemicals (see **Figure 13**).[117] Palmitoyl chloride and glyoxal were modified on carboxymethyl cellulose sequentially and 3,3′-dithiobis(propionohydrazide) was used as a cross-linker to assemble the nanogel. On the response of pH and redox stimulation, the nanogel showed reversible sol-gel transitions, indicating good pH- and redox-responsiveness. The nanogel loaded with agrochemicals was found to exhibit high loading capacity and various release behaviours.

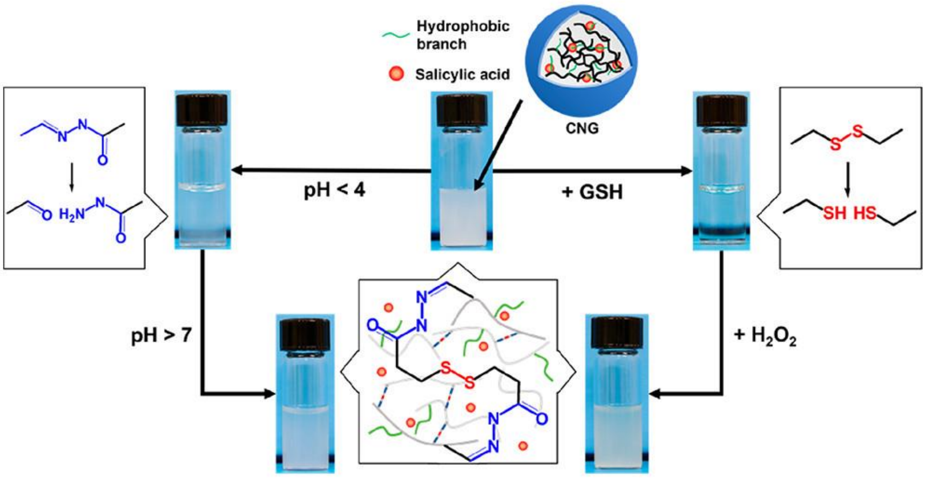

Figure 13. pH and redox dual-responsive behaviours of salicylic acid-loaded cellulose nanogels (CNG).[117]

In another study, to increase the effectiveness of the pesticide and enhance its adhesion to harmful targets, adhesive and stimulus-responsive nanocomposites were prepared using graphene oxide (GO) and polydopamine (PDA). The authors found that the release curve of hymexazol (fungicide) from the nanocomposite was NIR-laser-dependent and pH-dependent.[230] Currently, most of the stimuli-responsive carriers are synthetic, non-biodegradable materials because biopolymers and biocolloids are challenging to engineer. Nevertheless, effort should be made to build eco-friendly, smart nanocarriers using biodegradable materials through greener synthesis routes (e.g., pH-responsive lignin-based nanocapsules for controlled release of coumarin-6).[231] The ability of the engineered nanomaterials to control the delivery of pesticides and fertilizers can be affected by many factors. Characteristics that are highly desirable for such delivery systems include a slow and sustainable delivery rate and the ability to target given tissues or to act upon certain stimuli. Plant performance can be boosted by transporting the right nanomaterials to the right location, leading to the enhancement of the photosynthetic machinery or to induce self-defense mechanisms. New functions have been introduced in plants via nanobiotechnology.[232] The interest in nano-enabled agriculture is increasing, although the adoption of such precise, well-controlled, and often complicated technologies into large scale technical applications is still far from reality.[233]

For urban farming, strict hygienic practices must follow to minimize the risk of the introduction of pathogens and biological contamination into the growing space as well as removal of any residual contamination after harvesting.[155] Using advanced sensing technologies, one can closely monitor the crop for signs of pests or disease both manually and automatically using either a local- or remote-sensing system. This will help to detect, identify, and dispose of the diseased and infested plants.

2.6. Novel Materials for Non-destructive Plant Health Monitoring

Plant diseases and environmental stresses cause severe threats to both food security and the natural ecosystem by lowering crop yield and quality, reducing species diversity, and increasing human health risks.[234, 235] The shift from diverse, single-cycle traditional farming to genetically uniform, intensive urban farming systems has favoured the emergence of more virulent and host-specialized crop pathogens, which often cause large-scale outbreaks in agro-ecosystems with high planting densities.[236] Additionally, ensuring homogeneous growth conditions in urban farms as well as early and precise management of plant pathogens and stresses are even more critical to optimize agricultural output and protect food security.[155] Real-time plant health surveillance therefore plays an important role to augment crop yield and safety in urban agriculture.[236] As environmental stresses affect how solar radiation interacts with chlorophyll, leaves, and canopy, plants' spectral information can be monitored as a proxy of their health with remote sensing tools.[237, 238] These methods rely on plant trait measurements in terms of chlorophyll concentration, leaf surface area, temperature and water potential.[239, 240] Visible and near-infrared spectrometers have been coupled with unmanned aerial vehicles (UAV) to monitor plant diseases, water usage and nutrient deficiency non-destructively.[241] While these platforms can be used to interrogate plants' physical features remotely, they often rely on the manifestation of stresses to trigger plant phenotypic changes, rendering early diagnosis of crop health difficult.[239, 240]

An emerging class of materials for plant health surveillance detects signaling molecules propagated by plants upon stress perception. These stress signals range from short-lived molecules, phytohormones, and volatile organic compounds (VOCs), and their transduction triggers reprogramming of the cellular transcriptional machinery to enhance their fitness under stress.[21, 242] Monitoring these stress-induced signals as they are generated can unlock new opportunities for real-time crop health monitoring and early diagnostics of environmental stressors.[21, 242, 243] Single-walled carbon nanotubes (SWNT) have recently been used to monitor hydrogen peroxide (H_2O_2) signaling pathway elicited due to wounding, light stress, heat stress and pathogen infection in different plant species.[22] These nanosensors were embedded within the leaf mesophyll, and their near-infrared fluorescence was modulated upon contact with stress-induced H_2O_2. This fluorescence change could be monitored with a portable Raspberry Pi platform at a remote distance, opening possibilities for applications in urban agriculture. A photoelectrochemical sensor based on CdS/graphene oxide nanocomposite has also been used to detect indole-3-acetic acid, a key phytohormone involved in plant growth and adaptive responses.[23] Indole-3-acetic acid levels in seeds of wheat, corn, and soybean were successfully detected with a limit of detection of 0.05 ng/mL. Zheng *et al*. recently developed a paper-based colorimetric sensor array, using functionalized gold nanoparticles of different aspect ratios, for early and non-invasive detection of late blight in tomato leaves.[244] The smartphone-integrated platform could detect VOC emitted during *Phytophthora infestans* infection in a greenhouse setting as early as 2 days post-infection before visible symptoms were manifested, showcasing its potential utility for urban farming applications.

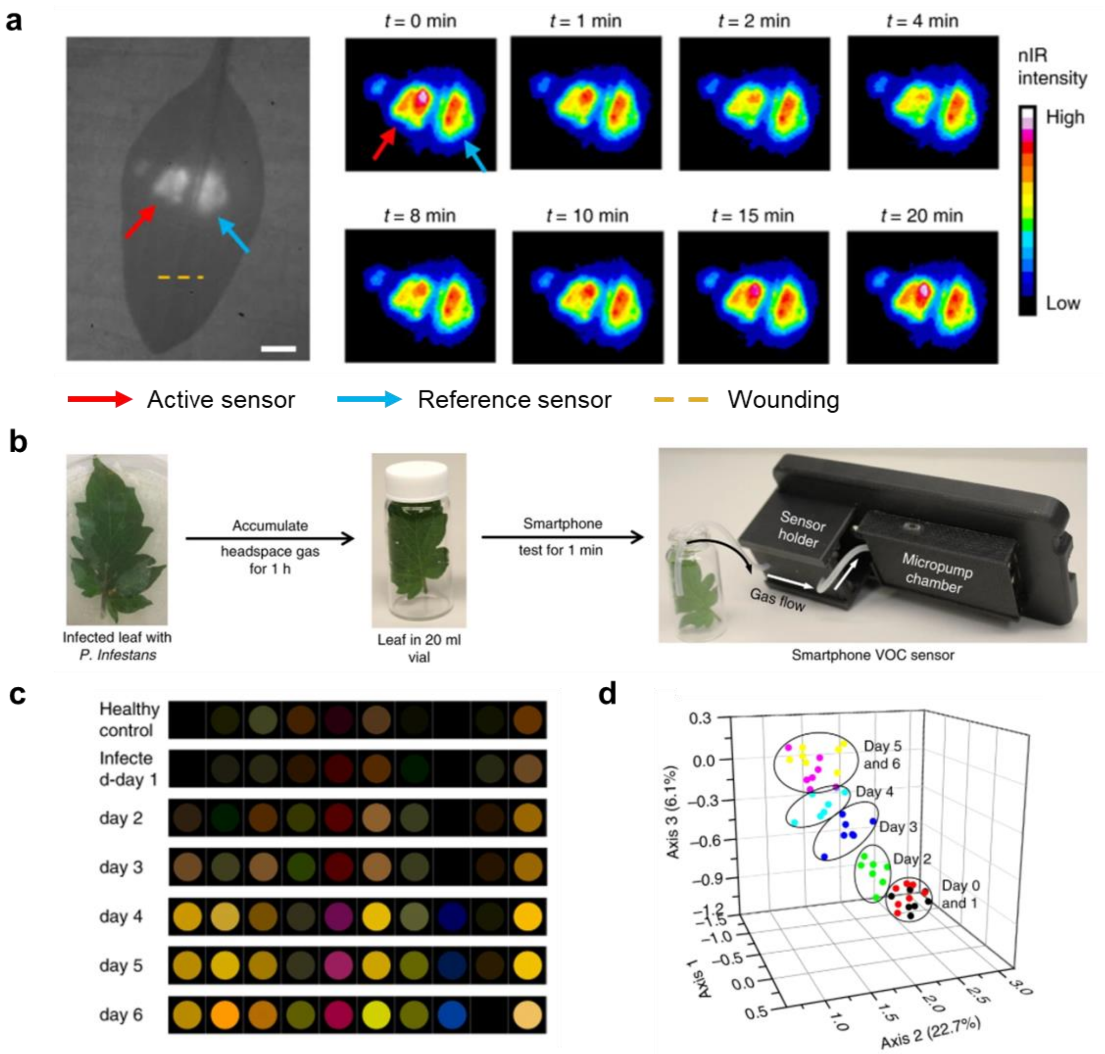

Figure 14. a) The application of SWNT nanosensors on intact spinach plant to monitor wound-induced H_2O_2 signaling pathway.[22] b) Analysis of Analysis of plant volatiles for plant disease

diagnostics using portable smartphone-integrated VOC sensing platform.[244] c) RGB profiles of VOC-sensing strips after *Pseudomonas Infestans* infection on tomato leaves, and d) their PCA score plot for different days post-infection.[244] a) Adapted with permission.[22] Copyright 2020, Springer Nature. b-d) Adapted with permission.[244] Copyright 2019, Springer Nature.

Besides monitoring these stress-induced signaling molecules, nanosensors could also be used to monitor environmental contaminants present in the belowground environment. Functionalized SWNT infiltrated into the leaf lamina could be used to detect arsenic pollutant taken up by the roots of various living plants such as rice, spinach, and fern.[245] Similarly, metal organic frameworks could be synthesized directly within a living plant to detect toxic metal ions and organic contaminants accumulated by the plant.[246] The readout of these SWNT- and MOF-based nanosensors could be obtained with a portable device such as a smartphone, paving way for the development of smart sensors for on-site environmental monitoring in agricultural systems. In the future, these nanoparticle-enabled platforms could be integrated with UAV and other remote sensing technologies to enable a large-scale field data collection for non-destructive plant health monitoring. These sensors can also be integrated as part of feedback control schemes within urban farms to continuously tune the optimal growth conditions with the ultimate goal of refining crop yield, nutrition, and culinary properties.[242] Such feedback control mechanisms with real-time plant health monitoring could contribute to next-generation urban farming with accelerated productivity and high modularity.

There are major challenges to overcome to unlock the full potential of novel sensors for plant health monitoring. The effect of these materials on the food chain or the possibility of their widespread release into the environment remains understudied despite recent technological progress in the field. Transformations and the fate of engineered materials will need to be investigated for proper risk evaluation.[247] Additionally, for *in vivo* sensors, information about their localization within plant tissues is needed to ensure that they are detecting the right metabolites at the right place. Another complication is that when these nanoparticles are introduced into the plant's biological environment, biomolecules such as proteins and carbohydrates can non-specifically adsorb on the nanoparticle surface, drastically altering the intended nanoparticle function through a process known as 'biofouling'.[248] This spontaneous corona formation can reduce nanosensors' sensitivity or change their subcellular distribution. Design strategies to minimize biomolecule adsorption have been pursued in nanomedicine and healthcare applications,[249-251] but it remains to be seen if they can be adapted to mitigate biofouling in plant systems.

3. Example of Urban Farming and Its Implications

3.1. Singapore Model

Singapore is a densely populated city (Figure 1b) and a major net food importer. This provides the perfect background for driving urban farming initiatives. At present, the country imports more than 90% of all its food supply and has less than 1% of its total land available for food production.[252] Currently, there are 5.8 million people living in Singapore and close to 80% of its population lives in public housing.[253] There is potential in using the rooftops of these housing blocks for larger scale farming plus the pockets of green spaces within the housing estates for small community farms and gardens. Singapore is moving towards increasing urban farming to increase local food production to meet the target of producing 30% of its food by 2030. Novel materials including nanostructured fertilizers, biopesticides, soilless substrates, water retention materials, and materials for light, temperature management and plant health monitoring systems will have a huge impact on the future development of urban farming in Singapore.

As one form of controlled environment farming, vertical farming has attracted great interest in Singapore. However, different companies employ slightly different environmental management techniques in pursuit of high productivity and better sustainability. For example, Sky Greens and the Agri-Food and Veterinary Authority of Singapore (AVA, now transferred to Singapore Food Agency and other statutory boards) developed a hydroponic technique consisting of revolving trays of vegetables around an aluminium tower (9 m in height) powered by a recycled water-pulley system that deploys rainwater collected from its overhead reservoirs (see **Figure 15**a).[254] This rotating system provides an equal distribution of sunlight, air flow and irrigation.[3] It harnesses natural sunlight and all organic waste is composted on the farm.[255] In contrast to Sky Greens, Sustenir Agriculture has developed a modular tower concept for their hydroponics using rolling and movable racks less than 3 m tall with plants packed tightly allowing for maximum light absorption from incorporated LED lights.[256, 257] The lights are integrated with sensors to allow for smart light management based on the relationship between photosynthetically active radiation[50] and biomass which correlates the absorbed photo energy and the biomass of the plants.[258] Novel materials and technologies, such as the implementation of automation – a robot cleaner or precise and smart light management, could greatly reduce the operational cost and increase the yield of farms (see Figure 15b-c).[254] The indoor vegetable farm in Panasonic Factory Solutions Asia Pacific has both soil cultivation and hydroponics. Through a system of automated seeding and potting, automated irrigation, an intelligent LED light system, controlled temperature, humidity and carbon dioxide, the farm is able achieve a high yield rate of 95% compared with traditional farming methods and is able to double its productivity since it started in 2013.

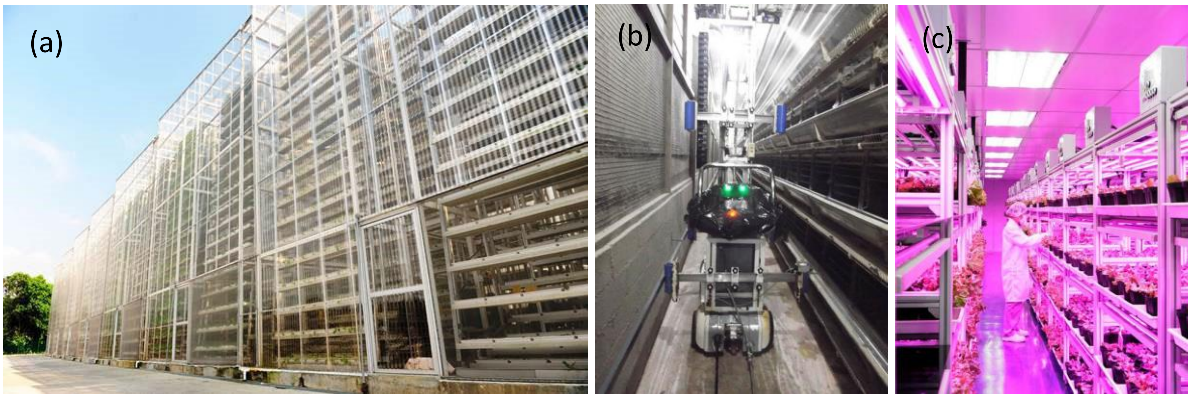

Figure 15. a) At Sky Greens, leafy vegetables are grown vertically in nine-metre-tall towers. b) A robot cleaner installed in a vertical farm to perform jobs previously done manually by workers. c) Indoor vertical farming illuminated with LEDs. AVA is working closely with farmers to adopt advanced farming systems and investing in innovative technologies.[254]

Beside controlled environment urban farming, rooftop farming is also popular in Singapore due to its tropical weather conditions. For example, a private enterprise called Edible Garden City that specialises in building urban gardens and providing consultancy to community farming initiatives was launched with the help of government support in 2012.[259] Since its establishment, it has built more than 200 edible gardens and transformed a former golf course into a permaculture community garden which grows 50 varieties of vegetables and herbs, tropical fruit trees and raises chickens which are used in the Open Farm Community restaurant's high-quality, organic dishes.[259] Other rooftop farming enterprises, such as Citiponics Farm@Ang Mo Kio, have also proven to be highly successful from a socio-economic perspective by providing employment to elderly residents in the nearby Housing & Development Board (HDB) blocks. In such settings where farms are located in a densely populated city, it is important to consider productivity and sustainability. Novel materials for the delivery of nutrients and pesticides, alternative substates and plant health monitoring systems can contribute towards making these farms more productive and sustainable.

3.2. Implications of the Singapore Model Worldwide

New technologies, including new advanced materials, for urban farming developed and test bedded in Singapore can be easily transferrable to other parts of the world. For instance, in a tropical hot and humid climate, it is difficult to grow temperate vegetables like lettuce. An aeroponic system originating from Singapore can provide a solution to overcome this constraint. This essentially makes used of an air-dynaponics system where the nutrient solution is cooled by making use of the Venturi nozzle effect. This provides a low-cost method to lower the temperature of the nutrient mixture for plant growth and at the same time ensure much higher dissolved oxygen content. This method has been successfully used to produce valuable greens like butterhead lettuce, Batavia lettuce, and Romaine lettuce for consumers.[259, 260] Another technology which can be adopted by other land scarce and tropical countries is Sky Green's "A-Go-Gro" technology where the crops are grown on a rotating tower powered by a recycled water-pulley system. This enables equal distribution of sunlight, air flow and irrigation and requires minuscule quantities of electricity, water and manpower. The A-Go-Gro system is suitable for tropical countries that receive an abundance of sunlight and water all year round but might not be suitable for countries with a seasonal climate.[255] In addition, from the successes of Singapore and other countries that promote urban farming, it can be seen that strong support from the government and collaboration between the private and public sectors are essential. The strong participation and support from the government provides the confidence that commercial companies need to invest in these urban farms.[255] New technological advances for urban farming can be made through academic institutions or university partnerships with industries to come up with innovative solutions in this emerging area. This model of strong collaboration between government, commercial companies and academic/research institutions can also be translated to other regions worldwide.

It is worth noting that other countries or cities in the world are also proactive in the practice and development of different forms of urban farming. Urban farming has obtained strong local government support, thus a wide range of urban agricultural activities occur in various cities in the world. For example, in New York city, many residents maintain small backyard gardens and also run community gardens.[261] Hundreds of non-profit farms which are built and maintained by students and residents are located around schools and housing around the city. They focus on food production and education, community empowerment, and increasing employment opportunities.[262] In contrast, the commercial urban farming business including indoor farming, hydroponics, and aquaponics focuses on technologically innovative and environmentally adaptable farming methods. They are producing high-quality food and developing new technologies for urban environment. Both types of urban farming help the city to expand its access to healthy food, building strong community networks, improving environmental conditions in neighbourhoods, and offering educational and job opportunities.

4. Future Perspectives and Outlook

Moving forward into the future, urban farming will become more important in delivering food to the growing urban population. There are some factors associated with these farming activities that limit their wider adoption and these are factors such as high initial capital cost requirement, small crop variety, high energy consumption, and sustainability of commercial urban farms. There are also several other challenges related to urban farming, namely, soil, air or water pollution, nanotoxicity, potential disease transmission to residents, and possible exposure to pesticides or herbicides. Pollution in the urban environment and agricultural businesses within flows in both directions. Just as urban soils which have been contaminated and are thus unsuitable for food production, urban farming itself can also introduce unwanted chemicals and agricultural waste into the environment.[263] Urban sewage and grey water carry detergents and dissolved chemicals and if they are used to water plants, the fruit and vegetables produced may contain more undesirable substances than rural produce. On the other hand, water supplies in the city can be polluted by inorganic fertilizers and manure, which result in undesirable proliferation of algae and aquatic plants in nutrient-rich waters. In addition, there is also cross-contamination between industrial areas, agricultural lots and residential areas. Polluted air containing nitrogen oxides, sulphur oxides, and hydrocarbons from traffic and industrial sectors can contaminate the urban farming products. Noxious smells or soil dust produced from farms also have a negative effect on the urban living environment. Furthermore, if novel materials such as nanomaterials or gene-editing reagents are used, biosafety concerns on nanotoxicity and non-target delivery cannot be ignored. Proper regulations and research should follow to reduce or eliminate the above-mentioned hazards.

Novel functional materials are pivotal for the shift from labour-intensive traditional farming practices to smart urban farming methods as this will help to mitigate some of the challenges discussed. Moving forward, materials innovation relating to efficient light and energy management, controlled delivery and other aspects relating to sensing would be highly relevant for the improvement of urban farming methods and technology. Future farming is dependent on more efficient use of resources (water, energy, manpower, etc.), availability of more sustainable energy sources (renewable energy) as well as waste reduction (waste up/recycling). As mentioned, materials innovation is central to many of these technologies, and it is important that data-driven decisions and machine learning (ML) algorithms should be developed to refine the way we design relevant materials and other urban farming systems.[264, 265] In this section, some perspectives on how materials technology can contribute towards future farms will be discussed.

4.1. Machine Learning-Assisted Optimization in Materials Design

Materials development making use of machine learning methodology speeds up the design and development of advanced energy materials as well as the discovery and deployment of other new materials.[266, 267] Here, the focus is on the discovery of new materials for renewable energy conversion, storage and artificial lighting which are important for the sustainability for urban farming. ML models have been developed to accelerate the discovery of new materials and optimize current materials (e.g., perovskites,[268, 269] inorganic materials,[270] organic materials,[271] inorganic-organic hybrid materials,[272] and electron donor-acceptor pairs[273, 274]). They can also be used to predict material properties (electronic properties of inorganic materials,[275] grain boundary energies,[276] phase transition of magnetic and superconducting materials[277] and crystal structures.[278] However, while there has been significant effort in the development and testing of ML models, more should be done to translate these findings to applications and better data collection should be carried out to include actual experimental data[279] as the bulk of literature focuses on prediction and calculation. The team led by Liu *et al*. reported the successful use of data from ML models (applying XGBoost-C) in optimizing chemical vapor deposition (CVD) synthesis of MoS_2 and hydrothermal synthesis of carbon quantum dots,[280, 281] both which have potential applications in sensors and optoelectronics for urban farming. Recent work by Wang *et al.* reports the construction and evaluation of several ML models (likewise using XGBoost) to successfully synthesize carbon quantum dot-based white LEDs with tuneable correlated colour temperature.[282] Similar approaches can thus be applied to lighting and sensors used in urban farming systems.

4.2. IoT-enabled Efficient Urban Farming Systems

Moving forward, well-implemented IoT and digital technologies will play a pivotal role in ensuring the long-term success and sustainability of urban farms. Urban farms equipped with IoT infrastructure can expect to run more effectively as they can provide monitoring, feedback and control for non-invasive and non-destructive 24/7 monitoring of plant growth and development, thus enabling real-time fine-tuning of the optimization process and data collection and analyses for building databases.[283, 284] As highlighted in Sections 2.4 and 2.5, optimizing growth conditions (lighting, humidity, temperature) and synchronizing species-dependent nutrient cycling and/or crop cycling all serve to maximize crop yields while minimizing materials waste and inefficient energy usage.[30]

Applying model-based digital twins (DT) for precision agriculture and urban farms is still in its infancy [283, 284] – the earliest publications only appeared within the past decade. The concept of using DT as decision support systems is not new; DT models have been adopted heavily by manufacturing industries, notably aerospace, as a “fail-safe” approach for testing decisions in virtual space due to zero tolerance for actual errors (both in terms of high cost and risk of catastrophic fatalities).[285-289] DTs are created for planning and control of otherwise conventional physical trials: sensors enabled by new materials in controlled growth environments provide real-time feedback to monitoring systems, which are then able to update simulation states of DTs in real-time to refine modelling accuracy and enable better predictions. DTs may be interconnected within an urban farming system depending on their purpose, while functioning individually as any of the following: virtual test-beds (imaginary DT), digital-mode real-time monitoring of plant growth and development (monitoring DT), digital projection of growth and development predictions (predictive DT), recommending corrective or preventive actions by machine learning and database referencing (prescriptive DT), autonomous remote operation (autonomous DT), archiving and compiling past data (recollection DT).[284] Predictive DTs may also be applied in the discovery and optimization of materials outlined in the preceding paragraphs; it is a versatile platform that finds application in relevant areas beyond those listed here. Regardless of their implementation in outdoor or indoor farms, the materials and digital technologies detailed thus far are inevitably intertwined in a continuous “test, feedback and optimization loop” and fundamental for driving precision agriculture and urban farming.

4.3. Materials Conversion Technologies to Close the Carbon Cycle: Recycling Waste to Feed Plants

Agricultural and food waste treatment methods such as burning or composting (discussed in Section 2.2.3) are common around the world, and these processes can help to recover some energy and return organic components back to the soil as fertilizers. Beside these waste treatment processes, to ensure sustainability in urban farming, alternative upcycling options can be explored, e.g., either by developing novel materials conversion technologies and improving conversion yields or adopting present technologies to include other untapped waste resources with potential contribution towards plant nutrition. For instance, a recent report by Lv *et al.* on $In(OH)_3$-assisted electrocatalytic coupling of nitrate and carbon dioxide to synthesize urea shows promising application as a sustainable source of nitrogen for plant uptake.[26] Another example is derived from nature – black soldier fly (“BSF” or *Hermetia illucens*) larvae can digest food waste and plastics via gut microbiota to form nitrogen-rich excretions that may be used as plant fertilizers.[27, 28] Such organic fertilizers do not have the pungent smells typical of organic fertilizers made from farm manure. Larvae farms also fit well into urban settings and are hence more suitable for urban farming, (e.g., Insectta, a Singaporean BSF larvae farm formed in 2018, produces dried BSF larvae and larvae frass as organic food and fertilizers respectively). Also, as mentioned in Sections 2.2.2 and 2.5, the effective recovery of cellulosic fibres from plant waste materials is pivotal to providing a key component of water, nutrient and pesticide delivery systems for improving soil health and buffering plant viability, especially under harsh or compromised growth conditions.

4.4. Economic, Political and Social Impact on Urban Farming

There has been a growing interest in urban farming worldwide due to a multitude of factors and some have been discussed in the introduction to this review. With the worldwide demographic shift towards urbanisation and the increasing threats to future food production due to environmental changes and land repurposing, the viability of urban farming is becoming more apparent. In the discussion so far, we have focused on the impact of advanced materials on urban farming. It is important to remember that the proliferation of such activities is often driven by economics and social needs and very much governed by country and local governmental policies. From the economics point of view, valuable urban land should be used for industry, commercial activities, or housing rather than urban farming. The non-market benefits such as civic and community engagement are often overlooked. In some urban poor regions such as East London, Tanzania and Nairobi,[290] such agriculture activities provide an excellent way for low-income group to access fresh produce and in some cases provide self-employment, encourage engagement of youths and provide a source of income. These activities should be initiated and driven by the community because of their local knowledge and understanding of the local needs.

For the urban rich, urban farming has a more altruistic goal and food security related angle to this. In some part of Europe such as Germany and in US states such as California and New York, urban farming serves to improve the livability of urban areas, social well-being and the diet of the communities.[291-293] In a land scarce and net food-importer country like Singapore, urban farming serves to provide food security. Governmental policies play a huge role in addressing complex and restrictive regulatory legislative framework relating to land use. Government-led initiatives and accelerator programmes that support the initial startup cost, provide support for sustainable development and the drive for a circular economy all play an important role in the realization of a successful urban farming model for a state or a country.[255, 293] Hence, for urban farming to dramatically change the food production landscape in the world it is important to develop technology, including advanced materials technology, that will improve productivity per unit space, lower capital investment, lower energy consumption during production, and generate fresher produce with higher nutritional value. This technology development together with an appropriate land use policy as well as community support will ensure the success of urban farming.

A high risk of errors in practice is inevitable especially in the early phase of smart materials/IoT development, adoption and refinement. Today, much of the crop-substrate-environment interactions are not yet well-understood, while threats of unpredictable changes in weather or other unforeseen disasters and crises may arise to upset the ecosystem and availability of materials and workforce. An interdisciplinary team of specialists in each of these areas can minimize and mitigate the risk of failure. A collective effort is required from stakeholders beyond farmers, scientists and researchers to ensure the abovementioned novel materials and digital technologies applied in urban farming and precision agriculture meet future global food production demands. Some considerations are:

(1) The collaboration between farmers (who know their land and crops well) and researchers (who know their materials and technology well) must be adequately supported financially by investors, government as well as the public, for initial running costs will be high (e.g., smart farm setup, green energy conversion and storage modules, electrical power demand from digital and operational processes).

(2) Long term efforts in this direction must continue to be supported nationally despite these challenges and even possible early failures while trying to "get it right", simply because we cannot afford not to. Premature withdrawal of support due to early failure does not merely halt progress in precision agriculture and its crop production; all prior effort, materials and expenses would also be laid to waste, setting the nation further back than before.

(3) Promotion of public awareness, education and involvement should be ramped up concurrently to correct misconceptions and address concerns within the community. Researchers from other disciplines (e.g., psychology, social sciences, communications) can provide insight from surveys and studies on public perception, purchase and consumption of modified or engineered foods,[294] such that we may work towards increasing public acceptance and support of technologies for precision agriculture and urban farming.

Our vision to increase food production through improving technologies used in urban farming is certainly possible with intelligent use of materials and better design of farming systems. According to the Food and Agriculture Organization of the United Nations' report in 2019 on the "State of the World's Biodiversity for Food and Agriculture", 66% of our global food demand was met by just 9 select crops.[295] Compared to leafy vegetables such as lettuces and *brassicas*, the cultivation of staple crops such as rice and wheat is significantly more land and water intensive in addition to having more stringent growth condition requirements and longer crop cycles. These are challenges that must be overcome to realize the vision of feeding the growing world population. This can be made possible through the development of materials that can directly impact plant growth or influence the environment of farms. As discussed earlier, with better use of data, further innovations can be expected. Fine-tuning of urban farming systems through smart design and the application of novel and advanced materials in species-specific crop growth – with the aim of decreasing materials costs and resource waste while optimizing harvest yields – will lead us closer to the goal of food security, nationally and globally.

In summary, we have discussed the impact that novel materials have on the development of urban farming. We have covered the use of such materials in seed enhancement, alternative substrates that have better water and nutrient retention, novel materials design for nutrient and pesticide delivery, materials the enable plant health monitoring systems and environmental management including water, light and temperature management, and waste management for urban farming. All these developments have enabled us to move towards the goal of achieving better environmental sustainability and higher harvest yields in urban farms. Singapore is an excellent example of a land-scarce city where food security is important and with governmental support and novel technologies, it is possible to achieve the goal of increasing food production with a range of sustainable, urban farming solutions. Based on these studies and advancements in novel materials research for urban farming, we foresee a huge prospect for the future development of urban farming which is accelerated by these novel materials and technologies that will enable more automation, better sensor integration in IoT in farms and machine learning to design better materials to meet the national and global food demands.

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Author Contribution:

L.X., M.Z., L.Z., T.T.S.L. and Y.M.L. discussed and designed the scope of manuscript.
L.X. and M.Z. contributed equally to this work.
All authors wrote and reviewed the manuscript.

Competing Interests

The authors declare no competing interests.

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TOC

Novel materials are key to accelerate the development of technologies to improve the productivity and ensure the sustainability of urban farming. The novel materials concepts that help in improving seed treatment, alternative substrates, nutrients or pesticide delivery, environmental management and plant health monitoring. This review highlights the current and potential research directions and challenges in these areas.

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TOC figure