Emerging and Disruptive Technologies for Urban Farming: A Review and Assessment

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Abstract. Increasing food demand in urban areas compounded with unsustainable conventional farming practices and reducing arable land has led to the development of urban farming. Urban farming techniques include vertical farming, indoor farming, hydroponics, aeroponics, aquaculture, and aquaponics. However, these methods alone cannot revolutionise farming; hence, they need to be coupled with technological innovations to reap their full potential and benefits. This paper reviews a variety of emerging and disruptive technologies introduced to urban farming, namely internet of things, automation, artificial intelligence, robotics, blockchain, digital twins, renewable energy, genetic modification, additive manufacturing, and nanotechnology. Each technology is discussed with regard to its applications, advantages, and disadvantages. Recommendations are also provided for future research and development.

1. Introduction

According to the United Nations’ Committee on World Food Security, food security is defined as when “all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life” [1]. By 2050, food demand is projected to increase by 59–98% in order to feed 9.7 billion people, of which 70% will be living in urban areas [2]. Conventional farming often adopts environmentally unsustainable practices, which can lead to deforestation, land degradation, environmental pollution, excessive water usage, and high carbon footprint [3]. The drawbacks of conventional farming, along with the fast reduction of arable land, give rise to the development of urban farming – a practice of cultivating, processing, and distributing crops and livestock in urban areas [4].

Urban farming techniques include vertical farming, indoor farming, hydroponics, aeroponics, aquaculture, and aquaponics. The concept of vertical farming is to farm up instead of farm out. Fish and vegetable crops in vertical farming are grown in vertically stacked layers on rooftops, building facades, or inside commercial or residential buildings, restaurants, grocery stores, greenhouses, warehouses, or shipping containers [5]. Hydroponics involves plants growing in soilless media where their roots are directly submerged in nutrient-rich solution [6], whereas aeroponics involves spraying nutrient-rich solution onto the plant roots periodically [7]. Aquaculture entails farming of fish and shellfish in all kinds of water environments. Aquaponics, on the other hand, combines aquaculture and hydroponics in a symbiotic closed-loop ecosystem [8]. Fish excretes wastes in the form of ammonia. The ammonia is converted into nitrite and then nitrate by nitrifying bacteria. The nitrate-enriched water is pumped to the
grow beds and provides natural fertiliser for the growth of plants. In return, the plants clean the water that flows back to the fish tanks.

Over the recent years, urban farming has revealed its superiority over conventional farming. To further realise the full potential and benefits of urban farming, new technological innovations are increasingly explored and implemented [3]. This paper, therefore, aims to review and assess various emerging and disruptive technologies for urban farming. The literature review is limited to English journal or conference papers published from 2015 to 2021 in popular academic research databases, namely Scopus, ScienceDirect, and IEEE Xplore. Figure 1 shows the breakdown of the number of papers by technologies: Internet of Things (IoT), automation, Artificial Intelligence (AI), robotics, blockchain, digital twins, renewable energy, genetic modification, Additive Manufacturing (AM), and nanotechnology.

2. Internet of Things (IoT)

IoT is a technological revolution and a driving force behind Industry 4.0 movement. It refers to an internet-connected network of multiple physical devices that can collect and share data with minimal human intervention [9]. The global IoT platform market size is projected to hit USD 13.310 billion by the end of 2026, with a compound annual growth rate of 28.5% in 2021–2026 [10].

A reliable and robust cyber-physical system with IoT is essential for urban farming. IoT sensor nodes acquire and transmit farm data to IoT gateways or edge devices. Subsequently, the data are transmitted to IoT cloud servers and computing services via appropriate wireless communication technologies (e.g., Wi-Fi and cellular) and messaging protocols (e.g., hypertext transfer protocol, message queuing telemetry transport, and constrained application protocol) for further processing and analysis [9,11,12]. Alibaba cloud, Amazon web services, Microsoft Azure, Google cloud platform, and IBM cloud are examples of cloud computing service providers. These software-as-a-service providers eliminate the requirement for farm operators to own a separate information technology department to manage and maintain cloud databases [13]. IoT dashboards and mobile applications can be utilised to remotely monitor crops in real time. Instant messaging software can be activated to send early warning alerts and notifications to farm operators so that immediate intervention can be done to prevent farm conditions from worsening [14]. Multiple IoT-enabled farms can exchange information and interact with one another [15].
IoT enables farm operators to remotely monitor their farm conditions in real time from anywhere at any time on any smart mobile devices [16,17]. IoT data analytics detects trends in data, extracts new insights on crop growth, livestock health, and potential process improvements, thereby facilitating effective problem solving and decision making with reduced human error [9,16]. Besides that, land, water, and energy resources can be optimised, and wastes can be lessened through IoT. However, IoT devices and networks are vulnerable to privacy and security violations. In addition, they are completely dependent on internet connection and power [4,11,13]. To save energy consumption in IoT and reduce carbon footprints, green IoT strategies and techniques can be considered, for example, reduction of network size, use of selective sensing, implementation of hybrid network architectures [18], as well as adoption of privacy-oriented blockchain-based solutions with consensus algorithms [19].

3. Automation

Automated systems are everywhere; they are fundamentally operated by comparing input signals with thresholds pre-set by the user. With the aid of a controller, these systems are pre-programmed to perform repetitive tasks [11]. Controllers are either programmable logic controllers or microcontrollers depending on the electrical load or complexity of the intended purpose [11,12]. Abnormalities are detected using sensors and rectified by controllers sending commands to actuators [20–23].

Agriculture involves multiple mundane and repetitive operations, making automation a perfect technology to improve urban farming processes. Hydroponics systems can be automated by deploying sensors to monitor environmental factors (e.g., air temperature, humidity, and light intensity). If any of these factors exceed the ideal conditions for crop growth, their corresponding actuators (e.g., air conditioners, ventilation fans, and grow lights) will automatically rectify the situation. For aquaculture and aquaponics systems, automatic fish feeders can be utilised [20,21]. Sensors for measuring pH, electrical conductivity, and ammonia determine if the water in the fish tank has reached toxic levels. If so, a pump will automatically expel and replenish fresh water into the tank [11,13]. Other monitorable factors include, but are not limited to, dissolved oxygen, water temperature, carbon dioxide, and wind velocity. With the incorporation of instant messaging and text services, farm operators can be promptly notified of any operation changes and alerted of any abnormal events [20–23].

Automating routine processes can significantly reduce manual labour. The implementation of fully automated farms can bring about entire farms managed by just a farm operator [13]. Furthermore, reduction of intervention by farm operators decreases the possibility of human error [11]. However, heavy reliance on sensors by automated systems increases the necessity for constant calibration and maintenance of sensors for accurate readings [11]. Simple automated farming systems cannot address the provision of fertilisers and pesticides in a sustainable way because these systems are not intelligent enough to decide the amount of chemicals required [24]. Therefore, it is crucial to integrate automated systems with other advanced technologies (e.g., IoT, AI, and robotics) to be more efficient and productive.

4. Artificial Intelligence (AI)

AI is a field of computer science that enables computers and machines to make decisions like human beings [25]. To make smart decisions independently, computers and machines need to be taught using machine learning (ML) algorithms; these algorithms can be broadly classified into four categories: supervised, unsupervised, semi-supervised, and reinforcement [26]. Examples of common ML algorithms are linear regression, logistic regression, support vector machines, Naïve Bayes, decision trees, random forests, k-nearest neighbours, k-means clustering, and artificial neural networks.

AI can analyse soil and water, as well as identify potential pests, weeds, and diseased plants so that proper irrigation, specific pesticides and fertilisers can be timely applied to plants that need treatments [11,25], hence decreasing yield loss and increasing farm productivity. On top of that, AI can predict fish and plant growth, as well as help schedule filtration maintenance and water replacement [14,27]. An AI machine powered by computer vision can comprehend and interpret the visual world. As such, it can automatically sort fish and plants, minimising manual food grading and quality checks [25].
AI removes the ambiguity of determining plant health via human judgement [25]. Precise utilisation of resources by AI helps lessen wastes and emissions in production [28]. Self-reliant urban farming systems cut down labour load on farm operators [13]. Data generated by AI can be shared among various farms to form a farming community for enhancing agricultural activities within a region. However, there is still no such rich database of AI-derived data and insights for farm operators [11,27]. Shortfalls of AI arise when datasets for training and test are limited or of poor quality [28]. Sensors damaged by environmental conditions produce inaccurate data. Low light, weather, obstruction by insects or plants, and foggy lenses affect the quality of digital images from cameras and videos [25]. Besides that, AI-driven machines are complicated and expensive.

5. Robotics

Robotics is the unity of mechanical, electrical, and computer engineering to fabricate machines that can perform complex tasks based on pre-programmed instructions [13]. Robots were first introduced as an innovative solution for industrial processes. As technology advances, robot cost and size reduce, and computing power increases; this gives rise to an escalating trend towards employing robots in many industries – agriculture, defence, logistics, medicine, professional cleaning, and space exploration, just to name a few [13].

Routine tasks, such as crop monitoring and watering, can be carried out by pre-programmed robots or drones. Required fertiliser or pesticide can be delivered to individual plants in a precise manner by robots [16]. Survey robots can travel through the farm floor to take measurements and feedback readings. The increased manoeuvrability of robots facilitates inspection tasks at tall vertical grow towers, for instance, checking the condition of crops and grow beds, and detecting the presence of plant diseases or insect pests [29]. Drones are capable of sustained flight; they can provide a top view of rooftop farms, as well as a deterrent to pests [16]. Aside from freely moving robots, fixed robotic arms have their niche in urban farming. Sensors measuring pH and electrical conductivity are prone to oxidation if prolonged submersion in water. Robotic arms can be programmed to dip sensors in fixed time intervals to obtain readings, extending sensor service life. Moreover, robotic arms can assist with sowing seeds and harvesting [13,28,30]. Thus, one farm operator can simultaneously manage a few farms with a fleet of robots.

Robots allow farm operators to monitor and manage farms without needing to move from their comfort. Tasks that pose hazards, such as handling chemicals and working at heights, can be easily managed by dispensable robots [29]. Furthermore, introducing robotics to agricultural industry creates job opportunities for robotics technicians and engineers. However, effective robots necessitate the fusion of IoT, AI, and global positioning systems. Urban farms close to residential areas have restrictions on drone flights due to noise and potential privacy breaches [31].

6. Blockchain

With the introduction of cryptocurrencies like Bitcoin, blockchain technology has elicited substantial attention from many industries. Moving away from a traditional centralised server, blockchain adopts a decentralised, open, cryptographically managed network of blocks to store information [16,32]. Each transaction is stored as a block. Every subsequent transaction is linked to the previous blocks using hashes, which results in a series of time-stamped records of all transactions ever made. This chain of information, which is impractical to tamper with, is shared with all users on the network [33].

Through blockchain, food can be traced back to the production farm, making food regulation more manageable and effective. One study demonstrated how mango from a Walmart could be traced from farm to consumer in 2.3 seconds via blockchain, where traditional methods would take more than a week [33]. Such transparency builds consumer-producer trust and attracts more investors to agriculture [32]. Blockchain also provides an efficient tamper-resistant avenue to track the food journey through the supply chain, while keeping the consistency of product ownership and reducing the need for inefficient crop certifications. Other product information (e.g., batch number and expiry dates) can be stored; this
addresses food safety, traceability, and quality, which in turn combat food fraud, safety recalls, and other supply chain inefficiencies [24,32].

Blockchain can bring about the concept of agricultural insurance where secured information can be brought down the supply chain, and prices can change according to the status of crop harvest, boosting financial support and lessening strain on farmer operators [32]. However, it greatly relies on radio frequency identification and IoT devices employed through the supply chain for data collection [33]. Being a relatively new technology, blockchain raises many concerns such as scalability, compatibility, power consumption, and implementation complexity [33,34].

7. Digital Twins
A digital twin is a virtual representation of a physical system [35]. It uses simulation and AI to mirror system properties and behaviours in real time, embodying all statuses and information of the physical system. Any changes in the physical system can be reflected by its digital counterpart. As such, a digital twin can illustrate how a physical system will react in different design alternatives and situations [35] and support decision making without the need to create prototypes [36].

With digital twins, farm operators need not be physically at agricultural site to monitor, control, coordinate, and execute farm operations [35]. Simulation of vertical grow bed layers in different configurations optimises building resources [36]. Virtual models of farm operating parameters (e.g., energy and water consumption) can guide farm operators in decision making, thereby maximising energy and water usage [36]. Aside from present data, historical data can be used for predicting system behaviours. Hence, digital twins can act as early warning systems when the predicted environment falls out of safe operating ranges. However, the implementation of digital twins for farming are complicated and demanding [35]. Most agricultural variables are associated with living organisms and are difficult to model and simulate accurately due to their intricate behaviours. In addition, modelling and simulation of seed fertility, fertilisers, pesticides, and pollution are challenging [14,37].

8. Renewable Energy
Solar energy and wind energy are two well-known clean and renewable energies [38]. Solar energy is produced by harnessing the radiating light and heat from the sun using photovoltaic (PV) panels. Conversely, wind energy is generated by harnessing air movement relative to Earth’s surface using wind turbines. Both solar and wind energies can be utilised to power electrical equipment in the farms, for example, air blowers, water pumps, air conditioners, ventilation fans, and grow lights [39]. Advanced PV panels that are transparent or semi-transparent can alter the wavelength of light as light passes through the panels to the plants. Selective plastic films can change the wavelengths according to optimal light absorption and plant growth [40].

Agrivoltaics combines crop cultivation and solar energy production with PV panels on the same land area [41]. The shade provided by the panels lowers plant surface temperature and evaporation, decreasing plant drought stress and increasing plant biomass production [42]. Concurrently, the plants reciprocate by keeping the panels cool and lowering panel heat stress.

Solar energy and wind energy can be further applied to produce hydrogen through the electrolysis of water. Green hydrogen is a promising clean and sustainable alternative to fossil fuels and can be a potential farm fuel to power urban farms [43]. However, the costs of hydrogen extraction, storage, and transportation are high. Moreover, hydrogen is highly flammable, which brings safety concerns.

9. Genetic Modification
Genetic modification is a cell manipulation technique. Specifically, the DNA of cells are modified by adding or removing gene sequences to bring out or suppress a trait in order to achieve a required outcome [3,4].

Genetic modification can be exploited to alter the characteristics of crops to bring out certain desirable traits. An example is modifying the crop gene such that the genetically modified plants are more inclined towards receiving light of wavelengths that match those emitted from the grow lights. As
a result, this can produce higher crop yields under artificial lights. Gene editing can also alter the growth temperature and humidity of crops to match the growth environment [5]. On top of that, plants can be genetically engineered to be more pathogen or pest resistant by editing plant pathogen receptors or removing recessive and susceptibility genes [44], which can potentially extend produce shelf life. However, consumers concern the safety of foods from genetically modified crops because they might cause long-term adverse effects on human health [45].

10. Additive Manufacturing (AM)
AM, also known as 3D printing, is building physical parts layer by layer from digital models [3,46,47]. It allows materialising complex designs that are impractical to manufacture using traditional methods. Plant pots, plant trays, mounting brackets, and light fixtures can be customised and created using AM [20,21]. Rapid prototyping can be employed to evaluate designs before mass production. Since infrastructure replacement parts can be manufactured in-house, farm operators can be more self-sufficient and trained, consequently lowering unnecessary supply chain and production costs.

In addition, AM can transform food production. Edible food can be produced in various enticing designs using different media (e.g., pureed turkey and celery paste) [46]. This versatility satisfies different diet requirements. Every household can own a 3D food printer and print what is needed, reducing food waste while fulfilling individual calorie needs. Moreover, 3D printed food can improve the lives of patients with dysphagia by enhancing food consistency and ease of swallowing [46]. However, extrusion printing requires transglutaminase to solidify meat after printing; excessive transglutaminase might raise health concerns among consumers [46].

11. Nanotechnology
Nanotechnology is the manipulation of nanomaterials with dimensions of less than 100 nanometres [48]. Nanoparticles have enhanced solubility, magnetic and optical properties, and catalytic reactivity [49]. In agriculture, pesticide and fertiliser are often applied in uncontrolled manners, which give rise to pesticide-resistant pathogens and pests. Furthermore, only a portion of it is absorbed by plants, while most of it is lost to the environment as pollution. Nanoencapsulated pesticides or fertilisers ensure that the optimal amount is administered to the plants, thus enhancing growth while lessening stress on the plants. Other benefits are increased germination success, improved root size and length, and enhanced photosynthetic and nitrogen metabolism activities [48,49].

Besides that, sensors built with nanomaterials, which convey information about nanoparticles, are small, portable, and sensitive [49,50]. Controlled environmental agriculture can be improved by using nanosensors to estimate crop harvest time, detect crop health, and determine microbial or chemical contamination on crops. Integration of nanosensors with global positioning system provides precision real-time monitoring of crops [49]. Nanomaterials with recommended doses may fail to deliver the desired results to the crops due to leaching and degradation of chemicals by photolysis and hydrolysis [49].

12. Conclusions
In this paper, various emerging and disruptive technologies for urban farming are reviewed and assessed. Based on the literature from 2015 to 2021, IoT, automation, and AI are the top three technological innovations that are extensively implemented and documented. In contrast, genetic modification, AM, and nanotechnology are relatively new and in their early adoption stage.

While IoT and AI are powerful technologies individually, the amalgamation of IoT with AI, together known as Artificial Intelligence of Things (AIoT), can make huge impacts on numerous urban farming activities and processes [51]. Coupled with the latest fifth generation (5G) wireless technology and environment-friendly technology, the green 5G-AIoT can potentially deliver a reliable and energy-efficient massive network of interconnected smart devices that are capable of self-monitoring, self-correcting, and self-healing themselves, thereby redefining the future of agriculture industry and other industries, as well as transforming businesses across industries.
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