# Farm Electrification: A Road-Map to Decarbonize the Agriculture Sector

Arash Farokhi Soofi, Saeed D. Manshadi, Araceli Saucedo*

*San Diego State University, United States*

**Abstract**

Electrification is a promising approach to most carbon-emitting sectors of economic sectors of human activities such as transportation and industry sectors. Electrifying the machinery and different systems used in a farm can mitigate the carbon footprint of the agriculture sector if renewable energy sources are coordinated with the agricultural loads appropriately. This paper presents a road-map that: 1) presents greenhouse gases emitting activities in the food supply chain, 2) the potential impact of vertical farming on the agriculture sector, 3) discuss the carbon footprint of different activities in the food supply chain, and 4) presents a road-map to decarbonize greenhouse gas emitting activities in farms. This paper estimates that electrification of farms in an appropriate process with renewable energy resources can decrease the carbon footprint of farming 44-70% depends on the type of the farm.

*Keywords:*
farm electrification, carbon footprint, supply chain, transportation, greenhouse emission, sustainable communities.

## 1. Introduction

Greenhouse gas (GHG) emissions from fossil fuels and land use have continuously grown since the 19*th* century after remarkable increase in utilizing machine resulted from the industrial revolution. Paris Agreement in 2015 set out an ambition to limit the global temperature increase to [1.5°-2°] above pre-industrial levels. However, these targets are hard to reach based on the current trends in emissions, planned infrastructure, and population growth [1]. Human activities that emit the most global GHGs emissions are electricity and heat production, industry, agriculture and other land-use, and transportation sectors. Agriculture, forestry, and other land-use sector accounted for 21% of GHGs emissions in the world in 2018 [2]. Fig. 1 shows the GHGs emissions by the economic sector between 1990 and 2019. The GHGs emissions of the transportation and agriculture sections increased 22.9% and 11.5% in the last 30 years, while the GHGs emissions of electricity and industry sections decreased 12.1% and 8.1% [3]. The increase of GHGs emissions of transportation and agriculture sectors is a result of the exponential increase of population and combustion engine vehicles.

The GHGs emissions come primarily from agriculture (i.e., cultivation of crops and livestock) and deforestation [4]. Several methods are used to study the global impact of human activities on earth. The concept of the carbon footprint originates from the ecological footprint, which

*Corresponding author
*Email address:* smanshadi@sdsu.edu (Arash Farokhi Soofi, Saeed D. Manshadi, Araceli Saucedo)

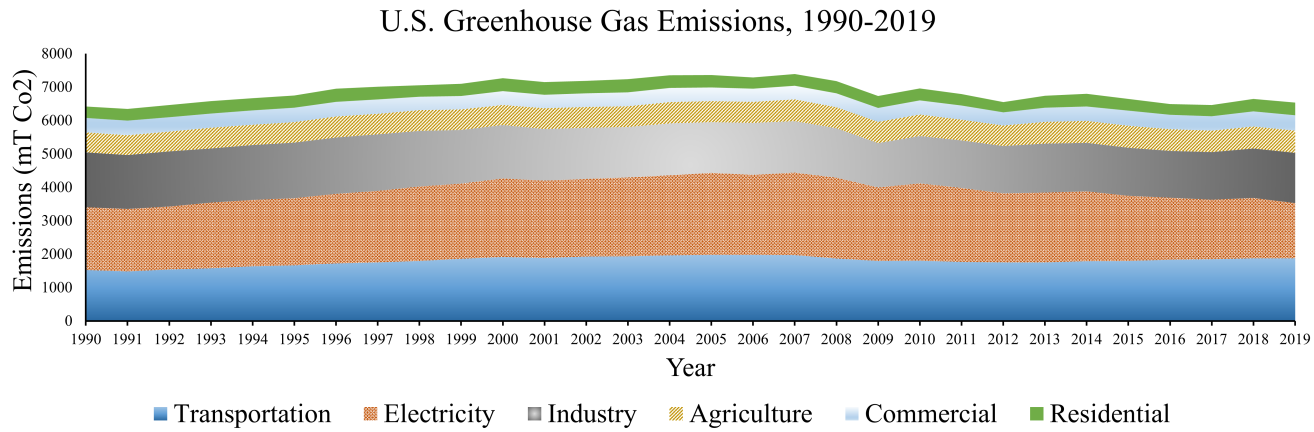


Figure 1: Greenhouse gas emitters in the U.S

was developed in the 1990s which estimates the number of "earths" that would theoretically be required if everyone on the planet consumed resources at the same level as the person calculating their ecological footprint [5]. A carbon footprint has historically been defined as "the total set of GHGs emissions caused by an organization, event, product or person." However, a more practicable definition has been suggested, and namely: "A measure of the total amount of carbon dioxide (CO2) and methane (CH4) emissions of a defined population, system or activity, considering all relevant sources, sinks, and storage within the spatial and temporal boundary of the population, system or activity of interest" [6].

After the industrial revolution, a large quantity of energy obtained from fossil fuels (e.g., coal and oil) has been widely used. Fossil fuels provide strong power for economic growth. However, substantial fossil fuels consumption emits a huge amount of GHGs. Mechanization of the agricultural industry led to the rapid growth of GHGs emissions of the agriculture sector [7]. Therefore, it is important to investigate the main factors accounting for the GHGs emissions of the agriculture sector to mitigate their environmental impact. Besides, the rapid world population growth in the recent decades will result in significant growth in food demand in the next 50 years. This increase in food demand will lead to the increase of carbon emissions from the agriculture sector. The GHGs emissions deteriorate the climate change in the world. Besides, Climate change decreases the resiliency and yield of conventional farms [8]. Thus, the GHGs emissions of the agricultural sector will increase substantially if the procedure of food supply isn't changed. 32% of food loss volume occurs in the agricultural production of the food supply chain [9, 10]. This volume accounts for 17% of the total GHGs emissions because of food loss in the food supply chain. The climate-smart agriculture (CSA) concept is introduced in [11] to mitigate the impact of climate change on the farms' yield, increase agricultural products sustainably, and reduce GHGs emissions.

This paper presents a road map to mitigate the GHGs emissions of agricultural production. The most carbon footprint of agricultural production originates from machinery usage, irrigation system, and pesticide actions. Machinery has a substantial role in every agricultural task on a farm. Electrifying tractors and other vehicles in a farm, irrigation system, and pesticide procedure with clean energy resources can mitigate the GHGs emissions of the agricultural activities. In [12], authors show that machinery accounts for 43.5% of the total energy inputs in farming. Utilizing renewable energy sources (RESs) to dispatch the electricity demand of these systems is vital to mitigating the carbon footprint of the agriculture sector. Thus, the coordination between RESs could play a vital role in this electrifying procedure. To this end, the rest of this paper is presented as follows. In Section 2, the food supply chain is described, and the GHGs emissions of tasks of each stage of the food supply chain are illustrated. In Section 3, the procedure to calculate the carbon footprint of conventional farming is elaborated. Then, the challenges and benefits of electrifying the most emitting tasks in a farm to reduce the carbon footprint of the agriculture sector are discussed. A decarbonization road-map for the conventional agriculture sector is presented in Section 4. Then, the concept of vertical farming as an alternative solution to the carbon emissions issue of the agriculture sector is presented and compared with conventional farming in different aspects in Section 5. Finally, the discussions are concluded in 6.

## 2. The Carbon Footprint of the Food Supply Chain

First, it is necessary to introduce the concept of the food supply chain or food system. The sequenced network of facilities and activities that support the production and delivery of food to consumers is called the food supply chain [13]. Fig. 2 shows the food supply chain where the arrows denote the flow of a product toward the consumer. Each part of the food supply chain includes tasks that are necessary to be done using equipment that emits GHGs. It is illustrated that the food supply chain has four main stages:

| Agriculture | Industry | Distribution | Consumption |
|---|---|---|---|
| Includes | | | |
| -Crop selection<br>-Land preparation<br>-Seed selection<br>-Soil preparation<br>-Sowing<br>-Irrigation<br>-Fertilization<br>-Pesticides<br>-Harvesting | - Transportation<br>- Processing<br>- Transportation<br>- Storage<br>- Packaging | -Transportation<br>- Storage<br>- Distribute to retailers and exporters | - Transportation<br>- Cooking |

Figure 2: Activities within the Food supply chain

- **Agricultural Production (Farming):**
  This is the place where meat, fruits, food, beverages, and other ingredients are produced. In the first stage, the crop is selected and the land is prepared using tractors, backhoes, and front-end loaders. All these machines emit GHGs and increase the carbon footprint of the produced food. In the next stage, after selecting seeds, the soil is prepared using tractors, cultivators, and plows. These machines have internal combustion engines and use fossil fuels. Irrigation, fertilization, and spraying are necessary for the growth of plants. These tasks are performed using irrigation, fertilization, and spraying systems to spray pesticides. The energy consumption of irrigation, fertilization, and spraying systems should be considered as source of GHGs emissions if the source of the electric power used by these systems is fossil fuels. At last, combine machines and cultipackers do the harvesting and packing tasks. Currently, these machines use fossil fuels to perform.

- **Processing and Manufacturing of the Final Product:**
  In this stage, products procured in the farm are processed into edible form. In the first step, products are transported to food manufacturing facilities to be processed. The transportation

of the food supply chain accounts for an essential portion of the environmental pollution. The impact of transport processes in terms of energy consumption, global warming, acidification, and eutrophication is studied in multiple articles [14]. There are innovative solutions to remove the transportation need via modern vertical farming that will be discussed later in this paper.

After processing and storage steps, the product is packaged in the manufacturing facility. Since the manufacturers are using the electrical power of the electricity grid, the energy consumption of the processes in the industry part should be calculated. One of the ways that can relate carbon footprint to energy consumption is to calculate the GHGs produced by a diesel generation unit to generate the same electrical energy needed. However, the carbon footprint of this stage is usually considered for the industrial carbon footprint as well.

- **Food Distribution:**
  Once the food is edible, it is transported and distributed to the retailers and suppliers. Distributors sell food, reduce costs, and do other actions to add to the value of the food. Transporting the product from industry to distributors adds to the total carbon emission of the product, as well. However, the carbon footprint of this stage is usually counted toward the transportation carbon footprint.

- **Food Consumption:**
  In this stage, consumers purchase edible products in stores. Preparing the food, which is called cooking, emits GHGs in this stage. However, the carbon footprint of this stage is usually counted toward the residential carbon footprint. It is worth noting that transportation plays a substantial role in transferring goods between stages of the food supply chain. However, the carbon footprint of the transportation of food is usually considered for the carbon footprint of the transportation sector.

Each year, the food supply chain utilizes about 19% of the total fossil fuel burned in the United States. 7% of this 19% is from agricultural production, 7% for processing, and 5% for distribution and food preparation by consumers [15]. It should be mentioned that in all these stages, some portion of food is lost during related processes. In [16], the authors presented the portion of food wastage in each food supply chain stage for developing and developed countries. Food wastage during different stages of the food supply chain increases the carbon footprint of the agriculture sector. The food supply chain is difficult to manage since it has time constraints to avoid spoilage, as well as concerns about contamination, high weight-to-value ratio, fragility, unique packaging requirement for each product, and the potential impact of food wastage. The challenges of the food supply chain are presented as follows.

- The cultivation of many foods is restricted by geography and temperature. Thus, the first challenge of the food supply chain related to agricultural production is nature dependency. For instance fruits, vegetables, and grains typically have fixed growing cycles with short and specific annual harvest periods. However, the demand for these products in North America and Europe doesn't fluctuate over a year. Thus, there are three options for supplying fresh produce that is out of season locally: 1) transferring from distant growing areas, 2) utilizing long-term storage, or 3) cultivating in a protected environment like a greenhouse or vertical farms. The first choice often results in lower carbon emissions than storing local product for several months [17, 18]. Higher emission of storing products not only results from the energy needed for climate control but also from the yield losses that occur during storage. Using a greenhouse is, even more, energy-intensive. For example, tomatoes produced locally in Swedish greenhouse require ten times as energy as tomatoes imported from Southern Europe [19]. Thus, long-distance supply chains, although they are energy-intensive, result in the lowest overall carbon footprint for providing out-of-season products to consumers.

- Similar foods are produced locally as well as imported from distant locations. In [20], authors illustrated that milk solids produced locally in the United Kingdom generate 34% more GHGs emissions than the same product imported from New Zealand, even with considering transportation.
- The third challenge is special handling to avoid yield loss and potential health issues of perishable products. Controlling the environment of these products during transportation and storage requires more energy usage which leads to more GHGs emissions. Besides, air transport is the only viable transportation option for these perishable products especially in the regions like Africa where no other alternative exists for transporting goods to the market [13].
- The location of facilities of industry stage can also impact the GHGs emissions. In [21], authors realized that the overall carbon footprint of the food supply chain was significantly reduced by locating the processing, storage, and packaging facilities in countries where more electricity is generated from RESs.

## 3. Carbon Footprint in Conventional Farming

The term carbon footprint has become a widely used term and concept in the public discussion on responsibility and preventing action against the threat of global warming. Its appearance tremendously increased in the public, and it became a buzzword across the media, the government, and the business world over the last decade. The carbon footprint term is rooted in the language of "Ecological Footprint" [5]. Ecological footprint referred to the biologically productive land and sea area required to sustain a given human population, expressed as human hectares [22]. The carbon footprint reflects the measure of the exclusive total amount of $CO_2$ emissions that are directly and indirectly caused by an activity or accumulated over the life stages of a product [23]. A similar term "climate footprint" was proposed in [23] to be used, if all the GHGs were included in the calculation instead of only $CO_2$. Carbon footprint, being a quantitative expression of GHGs emissions from an activity, helps in emission management and mitigation. By quantifying the GHGs emissions the source of emissions can be identified and areas of emission mitigation can be prioritized [24]. In this section, the carbon footprint of each section of conventional farming is discussed. In [6, 25, 26], authors presented methods to calculate the carbon footprint of various crops and dairy products. To calculate the carbon footprint, the amount of GHGs emitted or embodied in the life cycle of the product must be estimated. The life cycle of agricultural products starts from bringing raw materials and seeds to the final distribution of the product in stores. For the carbon footprint purposes, life cycle assessment estimates the GHGs emitted at each stage of the product's life cycle. It should be mentioned that different GHGs last in the atmosphere for different lengths of time, and they also absorb different amounts of heat. Since $CO_2$ has global warming potential value of 1, the GHGs emission data are translated into carbon dioxide equivalent ($CO_2$-e) using relating factors provided by IPCC [27, 28]. For example $1kg$ methane causes 25 times more warming impact over a 100 year period compare to $1kg$ of $CO_2$, and so $1kg$ methane is equivalent to 25 kg $CO_2$ [29]. There are multiple standards and guidelines available for greenhouse accounting. According to the current standards, the following procedure is suggested to calculate carbon footprint [30, 31]:

- Selection of GHGs
- Setting boundaries
- Collection of GHGs emission data
- Footprint calculation

The agriculture sector accounts for a vast portion of anthropogenic GHGs emissions and it is sensitive to many environmental and social factors. Thus, the development of an agriculture-specific carbon footprint calculation method is proposed in GHGs protocol publicly available specification (PAS) 2050 [31]. To facilitate convenient accounting, the following Tiers have been proposed [30, 32]:

- Tier 1: Direct emissions in the farm
- Tier 2: Consumption of energy originated from generators that consume fossil fuels
- Tier 3: All indirect emissions not covered under Tier 2, e.g. transportation of the product throughout the supply chain, waste disposal, processing product, etc.

Carbon footprint is divided into 2 parts: basic and full carbon footprint. Basic carbon footprint is presented in Tiers 1 and 2, while full carbon footprint includes all Tiers mentioned. Fig. 3 illustrates different activities involved in cultivation practices related to carbon footprint in a farm. Since agricultural soil can detain atmospheric $CO_2$ [33], it is considered as a part of Tier 1 in Fig. 3.

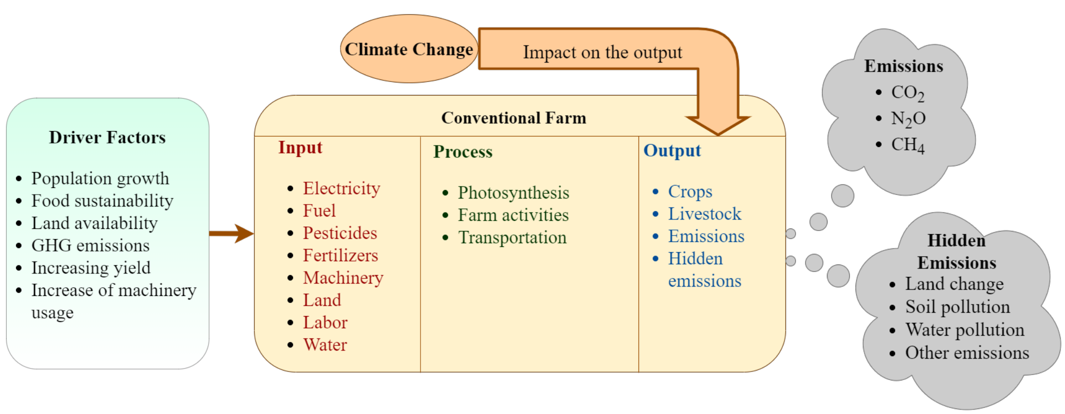


Figure 3: A generalized illustration of activities and inputs to a farm to be considered for basic carbon footprint of farm product

Since there is no agriculture-specific standard for carbon footprint calculation, the generalized standard three-Tier approach of the presented GHGs protocol is utilized here. The selection of boundary depends on the level up to which carbon footprints are to be calculated as presented in Table 1. For calculating the full carbon footprint in the production of crops such as cereals, vegetables, fruits, dairy, meat, etc., the activities related to cultivating the concerned crop and nourishing livestock up to the final readiness for use as raw material will be covered. To cover the activities up to the shelf of the store, activities like transportation, processing, packaging must be included as well. To calculate the full carbon footprints of food, the home preparations of food must be added. Extending the boundary of calculating carbon footprints of agricultural products beyond the farm's gate introduces activities like transportation of products, their distribution, and food preparation techniques. Analyses show that indirect emissions account for a significant part of the total carbon footprint of a product [34]. Thus, indirect emissions should be evaluated as well. Direct GHGs emissions to be covered for the agricultural systems include $CH_4$, $N_2O$, and $CO_2$ emissions from soil and $CO_2$ emissions from fossil fuel-power farm machinery such as tractors, harvesters, threshers, grain cleaning systems, cultivators, cultipackers, etc. Electricity usage for irrigation and spraying pesticides and fertilizers constitutes Tier 2 if the electricity generation mix doesn't include renewable generation units. It should be noted that labor activities are not considered under carbon footprint calculations. Agricultural soils can release $CO_2$ to the atmosphere. Thus, it is considered to be a part of Tier 1 in Fig. 3. In addition, agricultural inputs such as fertilizers, pesticides, herbicides, soil conditioners, and seeds carry embodied GHGs emissions. Thus, these inputs are considered as Tier 3. Table 1 illustrates the activities in a farm that constitute Tiers 1 and 2. It is worth noting that the source of electricity in Table 1 is not renewable generation units. Thus, the carbon footprint of the electricity should be calculated. However, coordinating RES with these electric loads mitigates Tier 2 emitters in the farm.

Table 1: Farm activities and their classification into Tiers [24]

| Activity | Cultivation practices | Energy source | Tier |
|---|---|---|---|
| Land Preparation | Plow | Diesel | 1 |
| | Horrow | Diesel | 1 |
| | Spader | Diesel | 1 |
| | Subsoiler | Diesel | 1 |
| | Spreader | Diesel | 1 |
| Sowing | Seed drill | Diesel | 1 |
| | Broadcast | Diesel | 1 |
| | Spreader | Diesel | 1 |
| | Transplanter | Diesel | 1 |
| Irrigation | Pump | Diesel/Electricity | 1/2 |
| | Channel | Diesel/Electricity | 1/2 |
| | Drip | Electricity | 2 |
| | Sprinkler | Electricity | 2 |
| Fertilization | Spreader | Diesel | 1 |
| | Self-propelled sprayers | Diesel | 1 |
| | Agricultural aircrafts | Gas | 1 |
| Pesticide application | Self-propelled sprayers | Diesel | 1 |
| | Agricultural aircrafts | Gas | 1 |
| Harvesting | Harvester | Diesel | 1 |
| Threshing | Thresher | Diesel | 1 |
| Seed processing | Seed processing systems | Diesel/Electricity | 1/2 |

The choice of boundaries for carbon footprint of agricultural products are as follows:

- Carbon footprint of cultivation: The boundary for this objective is up to farm gate.

- Carbon footprint of finished farm products: The boundary for evaluating the carbon footprint of this objective is up to shelf of stores.
- Carbon footprint of food: To calculate the carbon footprint of the food, the boundary should be up to the table in the houses.

In Table 2, the basic GHGs emissions and carbon footprint of different crops are presented. It should be noted that the units of total GHGs emissions and carbon footprint are kg $CO_2$-e per hectare and kg $CO_2$-e per $kg$ of product. It is illustrated that to produce 1 kg canola, 0.913 kg $CO_2$ equivalent is emitted.

Table 2: Average annual basic emissions and estimated carbon footprints of various field crops grown in the Dark Brown soil zone of a prairie [33]

| Crop | Total emission | Product's carbon footprint |
|---|---|---|
| Canola | 1,326 | 0.913 |
| Mustard | 515 | 0.652 |
| Flaxseed | 826 | 0.658 |
| Chickpea | 362 | 0.406 |
| Dry pea | 602 | 0.287 |
| Lentil | 245 | 0.237 |
| Spr. wheat | 1,145 | 0.533 |
| Means | 717 | 0.526 |

### *3.1. Transportation Carbon Footprint of Agricultural Products*

Transportation is the largest end-use sector toward global warming in the United States and other developed countries. Transportation has a major impact on the food sector since food is often shipped long distances in the food supply chain. In [35], authors estimate that near 40% of the U.S. agricultural production is exported. Another research shows that given a typical household food basket, transportation of food accounts for 11% of total carbon emissions associated with food production [36]. Transportation has a significant impact within the food and beverage sector since food is often shipped long distances and not infrequently via air. The emissions associated with transportation vary by origin and type of food. In [35, 36], the authors estimate that food transportation accounts for 50% of total carbon emissions for many fruits and vegetables. However, this number decreases to 10% for meat products. In [37], it is mentioned that about half of the food consumed in the U.S. is imported, and *the product cultivated in North America travels an average of 2,000 km from farm to the distribution sector*. Another way to transport products especially short life cycles products like luxury foods and flowers is air cargo. The U.S. Department of Energy reported that air transport accounts for 9% of the U.S. transport fossil fuel usage [13]. Although the transportation sector generally does not account for the carbon footprint of the food supply chain, it can play a significant role depending on the specific supply chain. In [13], authors show that the carbon equivalent ($CO_2$-e) emission of production and processing of food is approximately 7 times more than the one emitted by the transportation of food and cooking for plant-based and animal-based products in the United States.

## 4. Decarbonization of Conventional Farming

The electrification of machinery, irrigation, and pesticide systems in a farm mitigates the carbon footprint of the agricultural production section. It is deduced from [38] that electrification of machinery and these systems in the production stage can reduce the carbon footprint of the food up to 20%. Besides, electrifying the vehicles utilized for transporting products between different stages of the food supply chain can increase this number. The tools and vehicles that directly consume fossil fuels in the food supply chain are as follows.

- Machinery: Machinery has a major role in cultivating, growing, and harvesting crops on a farm. Tractors, all-terrain vehicles (ATV), utility vehicles (UTV), backhoes, and farm trucks (e.g., cultivator trucks, cultipacker trucks, and seed drills) are among those vehicles that are being used in a conventional farm. All of these vehicles emit GHGs if they keep using fossil fuels.

- Irrigation system: The irrigation system consists of huge gas-powered or electric water pumps that pump the water from wells, lakes, rivers, etc. Besides, there are different types of irrigation systems such as surface irrigation, sprinkler irrigation, micro-irrigation, etc. The type of irrigation system is dependent on site and situation factors.

- Pesticiding Systems: There are different ways to spray pesticides in a conventional farm. Airplane and machinery spraying are among those methods utilized in extensive farms. Although, today, in most farms the fertigation system is used. The fertigation system manages nutrients, pH, and pests in farms and nurseries by injecting fertilizers and pesticides directly into the irrigation system especially the sprinkler system.

- Transportation: The products produced in the farm mostly are transferred to the industrial facilities to be processed, packaged, and stored using trucks, trailers, ships, and airplanes. Then, these packaged products are distributed to the retailers using trucks. at last, consumers use their vehicles to buy these products in the shopping centers.

Electrifying these vehicles and systems mitigates the carbon footprint of the product of a farm. Utilizing electric vehicles instead of using traditional vehicles and trucks in a farm, increases the electricity demand of the farm. Most of the farms are far away from cities and electricity networks facilities. Thus, utilizing distributed energy resources (DERs) such as wind turbines and solar generation units is more cost-efficient in comparison with the construction of a transmission line for the farm. Besides, it mitigates the carbon footprint of the farm products. Coordination of DERs with these electric trucks, tractors, and systems is an important topic to investigate.

## 5. Vertical Farming as a Sustainable Alternative for Traditional Farming

Due to the exponential growth in the population of the world, fundamental changes are predicted to occur in the upcoming 50 years. The world population is predicted to reach to 9 billion by 2050 [39] and 80% of the population will reside in cities [40]. Thus, the demand for fresh food in cities will grow. The challenge of supplying sufficient food for everyone in a sustainable, efficient, and cost-effective way is rising significantly. Shedding the restrictions of seasonal weather patterns, natural disasters, change of temperature, water supply, and irradiance intensity, overcoming transportation challenges, and significantly enhancing yields, the growing trend of "vertical farming" could herald the future of food production [41]. For thousands of years, human populations have farmed the land for food. With the sharp increase of population on our planet over recent centuries as a result of the industrial revolution, increased living standards, and decreased mortality rates, the pressure on traditional farming has continually increased. While modern techniques have enhanced production rates, more than 11% of the total land of the world is now used for crop production [42].

Environmental challenges and issues of conventional farming range from habitat clearing to soil degradation and placing immense pressure on our planet's resources. Besides, with the expansion of cities, the distances between suitable farming land and the large populations who consume its products are growing and raising the impact of transportation. Adding to these challenges is climate change that is disrupting seasonal weather changes and the lack of cultivable soil near to rapidly expanding areas. One potential solution is the quite growing trend of vertical farming. A concept that sees the sprawling crop farms of old condensed into much smaller factory-like sites where conditions can be optimized and yields remarkably increased [43, 44]. The ultimate goal of vertical farming is to provide fresh food for the entire population of the world without concerning about climate changes and disasters [45].

Fig. 4 demonstrates a conceptual comparison between traditional and vertical farming. In vertical farms, almost everything from lighting and ambient temperature to soil conditions and nutrients is carefully monitored and controlled. These buildings utilize vertical racking to optimize space, as compared to a traditional crop farm enabling it to be located on a smaller site and much closer to an established urban area. Such facilities reduce the extent of haulage or food miles required to transport produce to consumers. Thus, vertical farms eliminate a significant portion of GHGs emissions in the food supply chain. Moreover, creating a controlled environment for crops to grow delivers many benefits. First, the process of crop production is insulated from seasonal weather patterns that are highly susceptible to distribution as a result of climate change. On a vertical farm, lighting, water, temperature, and humidity can be optimized to remove climatic risks and enhance production yields to more than 10 times that would receive through traditional farming methods. The use of a controlled environment also eliminates the losses from birds and insects that must be factored on conventional farms, eliminating the need for harmful pesticides to be used and improving the quality of produce. Pesticides account for 33% of the total carbon footprint of the agricultural production [38]. Thus, the elimination of pesticides in the vertical farms decreases the GHGs emissions of the agricultural production as well.

Vertical farms also optimize the level of nutrients that crops receive and solve the challenge of finding a sufficient extent of suitable farming land near a major urban area. In many instances, the soil is removed altogether and crops are grown on membranes where they are sprayed with nutrient-rich solutions. In Fig. 5, the machinery and systems needed in conventional and vertical farms are presented. Vertical farms need electricity to maintain such refined environments. While this concern is valid, vertical farms are powered by renewable generation technologies and recycle many of their resources.

Transportation of products in the food supply chain accounts for a large portion of the carbon footprint of the product depending on the type of the food. Since vertical farms are in the city and the food supply chain of the vertical farm is in the same building, the GHGs emission of transmission is eliminated in this method of farming. Besides, the need for utilizing heavy equipment in vertical farms is abolished. However, since in the vertical farms the environment is controlled, air conditioning, lighting, de/humidification systems are essential in the building. This controlled environment increases the yield by 100 times, decreases the water consumption to 1%, decreases the need for pesticides, and refines water and soil. Thus, vertical farming decreases the total carbon footprint of food.

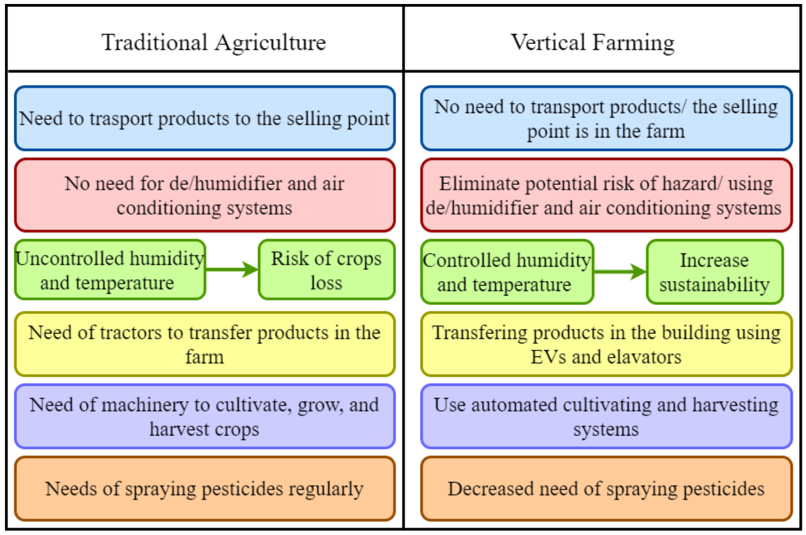


Figure 4: Conceptual comparison between traditional farming and vertical farming in terms of carbon emitting

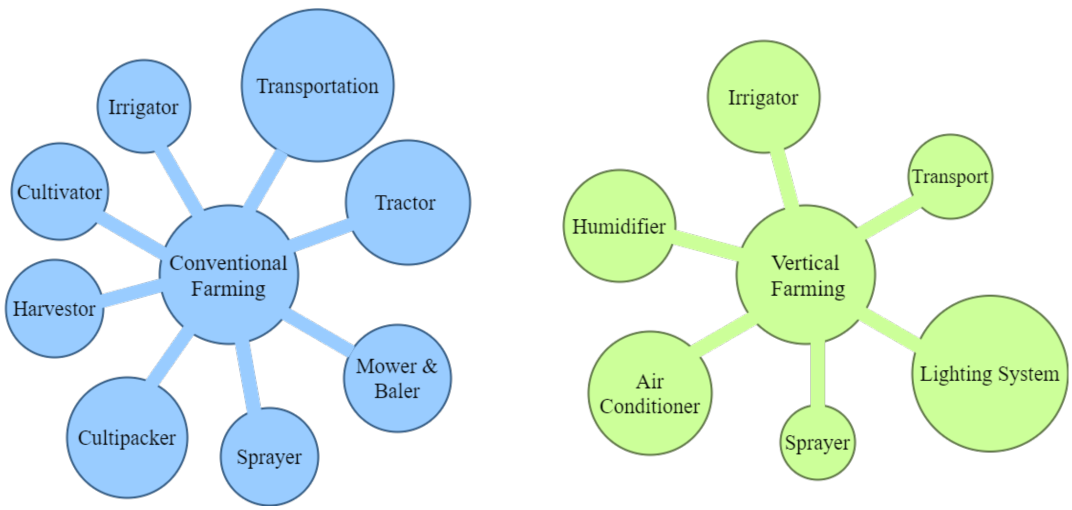


Figure 5: A comparison between the systems and tools utilized in conventional and vertical farms

In vertical farms, air conditioning, de/humidification, irrigation, and spraying systems typically use electricity. Thus, the carbon footprint of these systems should be calculated if their demanded electricity is not using renewable energy resources. The carbon footprint portion of these systems can be calculated using the relation between carbon footprint and energy consumption. Transportation in conventional farming consists of transporting goods from the farm to the industry section and transporting products from industry to distribution centers. However, transportation in the vertical farming method consists of transporting crops and goods in the building. All the heavy machines (e.g. tractors, cultivators, cultipackers, mowers, and balers) utilized in conventional farms use fossil fuels. However, all systems including transporting goods and crops in the vertical farms use electricity as the source of power. Note that manufacturing and processing products and distributing them are performed in the vertical farm building. Thus, there is no need to transport products thousands of kilometers to the selling point.

### *5.1. Energy Consumption in Vertical Farming*

The different systems needed in vertical farms which demand electricity are presented in Fig. 6. Adversaries of vertical farming raise a critical point and disadvantage which is how will plants

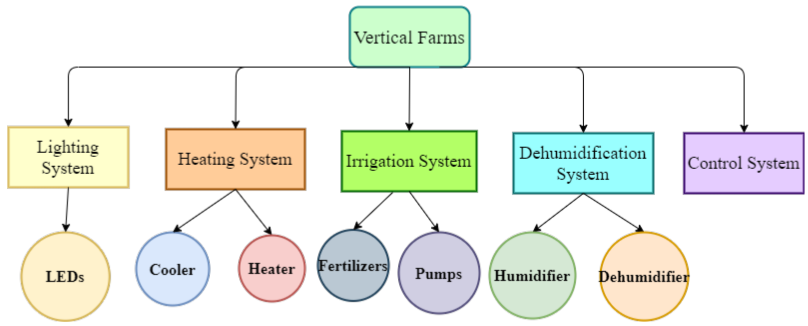


Figure 6: Different sections of vertical farms

grow inside a building with a sufficient amount of energy needed for growing plants [44, 46]. In vertical farms, the system uses both natural and artificial light. Due to the lack of solar irradiance in closed spaces, artificial lighting is the main source of energy within the building for photosynthesis, photoperiodic, and structure of plants [47]. The use of energy-efficient LED lighting reduces power consumption especially when they emit blue and red shades of light. The LED can be turned on and off as frequently as needed for the growth of plants. This helps to increase the yield of crops. Besides, it helps to further save energy and shave peak of electricity demand [48]. Thus, the coordination of vertical farms and other shiftable loads with distributed energy resources can mitigate the uncertainty of the electricity network. One of the major factors for increasing the growth of plants is air conditioning. In [46], authors suggest that the greenhouse can be used as a source of energy production to heat the building itself. Besides, plants keep the air around them cool by a phenomenon called evapotranspiration.

Another way that plants help to cool the temperature in large buildings is by providing shades. In [46], it is reported that vertical farms managed to cut down the amount of energy used in tall buildings up to 23% and reduce the air conditioning up to 20%. Therefore, vertical farming involves sustainable energy sources and power can be sent back to the electricity grid. Another crucial requirement for healthy plant growth indoors is humidity which requires diligent control to maximize the yield of crops and involves high energy costs. The optimized crop production process also allows vertical farmers to reduce the water usage amount, and many vertical farms are served by rainwater harvesting systems. The usage of such systems reduces the electricity demand of irrigation in vertical farms. Some vertical farms even collect and recycle the water that condenses within the controlled environment itself. This closed-cycle approach has the benefit of preventing nutrients and fertilizers from polluting the adjacent land rivers and decreasing the water and electricity usage for irrigation of crops. A system that controls all parts of the vertical farm is an essential part of these farms.

### *5.2. Vertical Farming in Sustainable Communities*

According to the Food and Agriculture Organization of the United Nations (FAO), 32% of all food produced in the world was lost or wasted in 2009 [49]. Food loss and wastage during different stages of the food supply chain can decrease the availability of food in the market and increase prices. As a result, the food access for low-income individuals will decrease. The food loss adversely impacts food security, the economy, and sustainability [16]. It is mentioned that vertical farming decreases the food loss that occurs in different stages of the food supply chain. Thus, utilizing vertical farms in countries where the major portion of their electricity power dispatches from renewable energy generation units, leads to the creation of a sustainable community. Sustainability is mainly defined as "people continuing to want to live in the same community, both now and in the future" [50]. Community is described as people living in the same geographical area and interacting socially with common ties and shared values [51, 52]. Sustainable communities meet the diverse needs of existing and future residents and their children contribute to the high quality of life and provide opportunity and choice. They achieve this in ways that make effective use of natural resources, enhance the environment, promote social cohesion and strengthen economic prosperity [53]. Thus, three dimensions of sustainable communities that need to be integrated into any sustainable community for ensuring a balance, mix, and sustain the existing community are presented economics, environment, and society.

The trade-off between electricity networks and vertical farms can create a sustainable community. In this sense, the electricity grid exchanges electricity with the vertical farm, and the vertical farm answers the need for food for the urban residents. Fig. 7 shows the sustainable community with the presence of vertical farms and electricity grid which its generation units are renewable energy resources. Vertical farms, electricity grids, and other parts of this community meet the diverse needs of existing and future residents of the community. This community is self-supported in terms of energy, food, and resources.

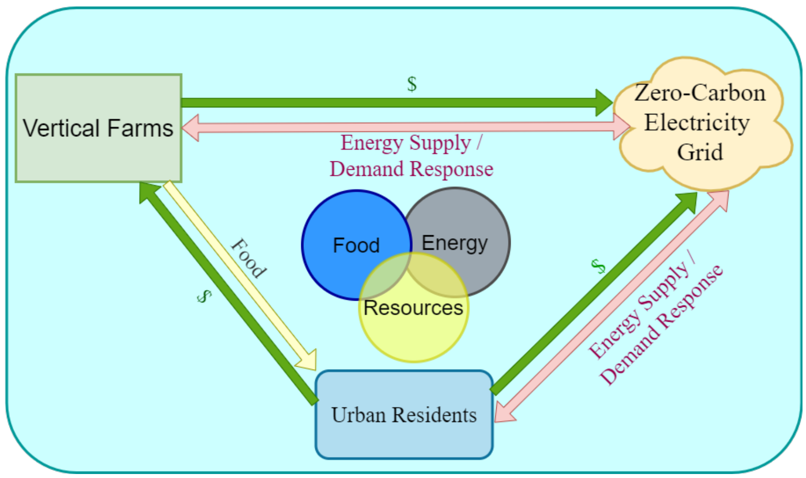


Figure 7: Sustainable Community

## 6. Conclusions

This paper presented a road-map to decarbonize the food supply chain and its stages. For different parts of the food supply chain, the top carbon emitters are distinguished. The food supply chain challenges that increase the carbon footprint of food are presented, and a way to remedy these challenges is presented. A thorough comparison between conventional and vertical farming is given, and the challenges and benefits of vertical farming are illustrated. The concept of sustainability of vertical farming and sustainable communities is presented. Besides, it is elaborated how vertical farming is essential for sustainable communities. The difference between GHGs emissions, carbon footprint, and carbon equivalent emissions terms is essential to calculate the carbon footprint of each economic sector. Farm activities that directly emit GHGs are distinguished, and a discussion to decarbonize these activities is mapped.

## References


[1] N. Höhne, M. den Elzen, J. Rogelj, B. Metz, T. Fransen, T. Kuramochi, A. Olhoff, J. Alcamo, H. Winkler, S. Fu *et al.*, "Emissions: world has four times the work or one-third of the time," 2020.

[2] W. F. Lamb, T. Wiedmann, J. Pongratz, R. Andrew, M. Crippa, J. G. Olivier, D. Wiedenhofer, G. Mattioli, A. Al Khourdajie, J. House *et al.*, "A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018," *Environmental Research Letters*, 2021.

[3] "Greenhouse gas emission — united states environmental protection agency," https://cfpub.epa.gov/ghgdata/inventoryexplorer/#allsectors/allsectors/allgas/econsect/all, (Accessed on 08/25/2021).

[4] F. Tubiello, M. Salvatore, R. Cóndor Golec, A. Ferrara, S. Rossi, R. Biancalani, S. Federici, H. Jacobs, and A. Flammini, "Agriculture, forestry and other land use emissions by sources and removals by sinks," *Rome, Italy*, 2014.

[5] M. Wackernagel and W. Rees, *Our ecological footprint: reducing human impact on the earth.* New society publishers, 1998, vol. 9.

[6] L. A. Wright, S. Kemp, and I. Williams, "'carbon footprinting': towards a universally accepted definition," *Carbon management*, vol. 2, no. 1, pp. 61–72, 2011.

[7] B. Lin and B. Xu, "Factors affecting co2 emissions in china's agriculture sector: A quantile regression," *Renewable and Sustainable Energy Reviews*, vol. 94, pp. 15–27, 2018.

[8] J. Wang, S. K. Vanga, R. Saxena, V. Orsat, and V. Raghavan, "Effect of climate change on the yield of cereal crops: a review," *Climate*, vol. 6, no. 2, p. 41, 2018.

[9] A. M. Loboguerrero, B. M. Campbell, P. J. Cooper, J. W. Hansen, T. Rosenstock, and E. Wollenberg, "Food and earth systems: priorities for climate change adaptation and mitigation for agriculture and food systems," *Sustainability*, vol. 11, no. 5, p. 1372, 2019.

[10] "Food wastage footprint — impacts on natural resources—summary report; fao: Rome, italy, 2013," http://www.fao.org/3/i3347e/i3347e.pdf, (Accessed on 09/17/2021).

[11] "Climate smart agriculture source book — food and agriculture organization of the united nations," http://www.fao.org/climate-smart-agriculture-sourcebook/concept/modulea1-introducing-csa/chapter-a1-2/en/, (Accessed on 09/17/2021).

[12] S. Deike, B. Pallutt, and O. Christen, "Investigations on the energy efficiency of organic and integrated farming with specific emphasis on pesticide use intensity," *European Journal of Agronomy*, vol. 28, no. 3, pp. 461–470, 2008.

[13] W. Wakeland, S. Cholette, and K. Venkat, "Food transportation issues and reducing carbon footprint," in *Green technologies in food production and processing.* Springer, 2012, pp. 211–236.

[14] P. Konieczny, R. Dobrucka, and E. Mroczek, "Using carbon footprint to evaluate environmental issues of food transportation." *LogForum*, vol. 9, no. 1, 2013.

[15] D. Pimentel *et al.*, "Impacts of organic farming on the efficiency of energy use in agriculture," *An organic center state of science review*, pp. 1–40, 2006.

[16] B. Lipinski, C. Hanson, R. Waite, T. Searchinger, J. Lomax, and L. Kitinoja, "Reducing food loss and waste," 2013.

[17] A. Hospido, L. M. i Canals, S. McLaren, M. Truninger, G. Edwards-Jones, and R. Clift, "The role of seasonality in lettuce consumption: a case study of environmental and social aspects," *The International Journal of Life Cycle Assessment*, vol. 14, no. 5, pp. 381–391, 2009.

[18] L. M. i Canals, S. J. Cowell, S. Sim, and L. Basson, "Comparing domestic versus imported apples: a focus on energy use," *Environmental Science and Pollution Research-International*, vol. 14, no. 5, pp. 338–344, 2007.

[19] A. Carlsson-Kanyama, M. P. Ekström, and H. Shanahan, "Food and life cycle energy inputs: consequences of diet and ways to increase efficiency," *Ecological economics*, vol. 44, no. 2-3, pp. 293–307, 2003.

[20] C. M. Saunders and A. Barber, "Comparative energy and greenhouse gas emissions of new zealand's and the uk's dairy industry," 2007.

[21] S. Sim, M. Barry, R. Clift, and S. J. Cowell, "The relative importance of transport in determining an appropriate sustainability strategy for food sourcing," *The International Journal of Life Cycle Assessment*, vol. 12, no. 6, pp. 422–431, 2007.

[22] M. S. Mancini, A. Galli, V. Niccolucci, D. Lin, S. Bastianoni, M. Wackernagel, and N. Marchettini, "Ecological footprint: refining the carbon footprint calculation," *Ecological indicators*, vol. 61, pp. 390–403, 2016.

[23] T. Wiedmann and J. Minx, "A definition of 'carbon footprint'," *Ecological economics research trends*, vol. 1, pp. 1–11, 2008.

[24] D. Pandey, M. Agrawal, and J. S. Pandey, "Carbon footprint: current methods of estimation," *Environmental monitoring and assessment*, vol. 178, no. 1, pp. 135–160, 2011.

[25] V. Vasilaki, E. Katsou, S. Ponsá, and J. Colón, "Water and carbon footprint of selected dairy products: A case study in catalonia," *Journal of Cleaner Production*, vol. 139, pp. 504–516, 2016.

[26] Y. Gan, C. Liang, C. Hamel, H. Cutforth, and H. Wang, "Strategies for reducing the carbon footprint of field crops for semiarid areas. a review," *Agronomy for Sustainable Development*, vol. 31, no. 4, pp. 643–656, 2011.

[27] "Ar5 climate change 2014 — mitigation of climate change," https://www.ipcc.ch/report/ar5/wg3/, (Accessed on 08/25/2021).

[28] H. Lee, "Intergovernmental panel on climate change," 2007.

[29] M. Brander and G. Davis, "Greenhouse gases, co2, co2e, and carbon: What do all these terms mean," *Econometrica, White Papers*, 2012.

[30] W. WBCSD, "The greenhouse gas protocol," *A corporate accounting and reporting standard, Rev. ed. Washington, DC, Conches-Geneva*, 2004.

[31] P. A. Specification *et al.*, "Specification for the assessment of the life cycle greenhouse gas emissions of goods and services," *Bsi Br. Stand. Isbn*, vol. 978, p. 580, 2008.

[32] D. Pandey and M. Agrawal, "Carbon footprint estimation in the agriculture sector," in *Assessment of Carbon Footprint in Different Industrial Sectors, Volume 1.* Springer, 2014, pp. 25–47.

[33] R. Lal, "Carbon emission from farm operations," *Environment international*, vol. 30, no. 7, pp. 981–990, 2004.

[34] H. S. Matthews, C. T. Hendrickson, and C. L. Weber, "The importance of carbon footprint estimation boundaries," 2008.

[35] M. C. Heller, G. A. Keoleian *et al.*, *Life cycle-based sustainability indicators for assessment of the US food system.* Center for Sustainable Systems, University of Michigan Ann Arbor, MI, 2000, vol. 4.

[36] C. L. Weber and H. S. Matthews, "Food-miles and the relative climate impacts of food choices in the united states," 2008.

[37] R. S. Pirog, T. Van Pelt, K. Enshayan, and E. Cook, "Food, fuel, and freeways: An iowa perspective on how far food travels, fuel usage, and greenhouse gas emissions," 2001.

[38] G. Todde, L. Murgia, M. Caria, and A. Pazzona, "A comprehensive energy analysis and related carbon footprint of dairy farms, part 2: Investigation and modeling of indirect energy requirements," *Energies*, vol. 11, no. 2, p. 463, 2018.

[39] C. Banerjee and L. Adenaeuer, "Up, up and away! the economics of vertical farming," *Journal of Agricultural Studies*, vol. 2, no. 1, pp. 40–60, 2014.

[40] D. Despommier, "Farming up the city: the rise of urban vertical farms," *Trends in biotechnology*, vol. 31, no. 7, pp. 388–389, 2013.

[41] F. Kalantari, O. Mohd Tahir, A. Mahmoudi Lahijani, and S. Kalantari, "A review of vertical farming technology: A guide for implementation of building integrated agriculture in cities," in *Advanced Engineering Forum*, vol. 24. Trans Tech Publ, 2017, pp. 76–91.

[42] "Crop production and land use — agricultural land nations," http://www.fao.org/3/y4252e/y4252e06.htm, (Accessed on 09/17/2021).

[43] P. Platt, "Vertical farming: An interview with dickson despommier," *Gastronomica*, vol. 7, no. 3, pp. 80–87, 2007.

[44] M. Al-Chalabi, "Vertical farming: Skyscraper sustainability?" *Sustainable Cities and Society*, vol. 18, pp. 74–77, 2015.

[45] F. Kalantari, O. M. Tahir, R. A. Joni, and E. Fatemi, "Opportunities and challenges in sustainability of vertical farming: A review," *Journal of Landscape Ecology*, vol. 11, no. 1, pp. 35–60, 2018.

[46] S. Thomaier, K. Specht, D. Henckel, A. Dierich, R. Siebert, U. B. Freisinger, and M. Sawicka, "Farming in and on urban buildings: Present practice and specific novelties of zero-acreage farming (zfarming)," *Renewable Agriculture and Food Systems*, vol. 30, no. 1, pp. 43–54, 2015.

[47] J. Germer, J. Sauerborn, F. Asch, J. de Boer, J. Schreiber, G. Weber, and J. Müller, "Skyfarming an ecological innovation to enhance global food security," *Journal für Verbraucherschutz und Lebensmittelsicherheit*, vol. 6, no. 2, pp. 237–251, 2011.

[48] V. M. Perez, *Study of the sustainability issues of food production using vertical farm methods in an urban environment within the state of Indiana.* Purdue University, 2014.

[49] A. Organization and I. F. for Agricultural Development, *Gender in agriculture sourcebook.* World Bank Publications, 2009.

[50] D. Long and M. Hutchins, *A toolkit of indicators of sustainable communities:(Formerly a toolkit of sustainability indicators).* European Institute for Urban Affairs, 2003.

[51] D. E. Poplin, *Communities: A survey of theories and methods of research.* Macmillan Publishing Company, 1979.

[52] R. Kasim, A. R. Ahmad, and S. Eni, "The neighbourhood facilities and the sustainable communities agenda: an overview," *University Tun Hussein Onn Malaysia*, 2007.

[53] G. B. O. of the Deputy Prime Minister (ODPM), *The Egan review: skills for sustainable communities.* Office of the Deputy Prime Minister, London, England, 2004.