sustainability

MDPI

Review

Rooted in Nature: The Rise, Challenges, and Potential of Organic Farming and Fertilizers in Agroecosystems

Dinesh Panday [1,†], Nikita Bhusal [2], Saurav Das [3,*,†] and Arash Ghalehgolabbehbahani [4]

[1] Rodale Institute, Pocono Organic Center, Long Pond, PA 18610, USA; dinesh.panday@huskers.unl.edu
[2] Food Science and Human Nutrition, University of Florida, Gainesville, FL 32611, USA; bhusalnikita@ufl.edu
[3] Department of Agronomy and Horticulture, University of Nebraska, Lincoln, NE 68543, USA
[4] Rodale Institute, Kutztown, PA 19530, USA; arash.ghale@rodaleinstitute.org
* Correspondence: sdas4@unl.edu
† These authors contributed equally to this work.

Abstract: Organic farming, which is deeply rooted in traditional agricultural practices, has witnessed a profound evolution over the last century. Transitioning from a grassroots initiative resisting the industrialization of agriculture to a global industry, organic farming now plays a pivotal role in addressing contemporary challenges related to environmental health, sustainability, and food safety. Despite the growing consumer demand for organic products and market access, organic farming has its challenges. This paper discusses the origin and evolution of organic farming with an emphasis on different types of organic fertilizers, benefits, and challenges. Nutrient variability and the slow-release nature of organic fertilizer often do not meet crop demands and can substantially reduce yield. Some organic fertilizers, like manure and biosolids, can provide a higher yield benefit, but there are environmental and health risks associated with them. Weed and pest management in organic farming can be labor-intensive and increase costs. Inefficient planning of organic farming and rapid transition can also create food insecurity. This paper also gives a brief account of the current certification process for organic fertilizers and their technicalities. It showcases how the holistic approach of organic farming extends beyond production, including strategies like reducing food waste and building self-sufficient farming communities. These practices contribute to a more sustainable agricultural system, reducing environmental impacts and supporting local economies. Future technological innovations, especially in precision agriculture and bio-physicochemical models, can help in formulating targeted organic fertilizers.

Keywords: organic farming; Organic Materials Review Institute; organic fertilizers; regenerative agriculture; soil health

check for updates

Citation: Panday, D.; Bhusal, N.; Das, S.; Ghalehgolabbehbahani, A. Rooted in Nature: The Rise, Challenges, and Potential of Organic Farming and Fertilizers in Agroecosystems. *Sustainability* **2024**, *16*, 1530. https://doi.org/10.3390/su16041530

Academic Editors: Ioannis Roussis and Ioanna Kakabouki

Received: 3 January 2024
Revised: 8 February 2024
Accepted: 9 February 2024
Published: 11 February 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Organic production systems integrate cultural, biological, and mechanical practices to promote the cycling of resources, ecological balance, and biodiversity conservation. With rising environmental concerns and health awareness, there is a surge in consumer demand for fresh organic products. This demand is evident as organic fruit and vegetable sales in the United States account for 15% of all retail produce sales, with USD 60 billion in revenue generated in 2022 [1]. Studies suggest that nature-friendly organic farming systems prove more lucrative for farmers than their chemically intensive counterparts [2,3]. This profitability arises because organic farmers predominantly rely on ecosystem services to achieve high crop yields, whereas conventional farmers rely heavily on external inputs [4,5]. Premium prices on organic food are another aspect of higher benefits that can compensate for the lower yields, yet the consumer impact remains a subject of debate. Despite its popularity and profitability, organic farming is not without challenges. Farmers must grapple with issues like organic nutrient sourcing, limited nutrient contents of organic fertilizers, insect pests, and pathogens and require extensive knowledge in crop and soil management [6].

The organic production system relies on organic fertilizers. Huntley et al. (1997) defined organic fertilizers as naturally occurring mineral sources that undergo minimal human intervention, mainly through physical extraction [7]. They can be broadly categorized into mineral and rock products, animal products, and plant products. However, they often release nutrients slowly, and their nutrient availability can be unpredictable. For instance, composted organic materials only release 1–3% of their total nitrogen (N) annually [8]. To address these concerns, the market now offers a variety of organic substrates and commercial fast-releasing organic fertilizers. Vermicompost, for instance, provides higher nutrient levels than traditional compost [9]. Commercial organic fertilizers are available in dry (e.g., bone meal, blood meal) and liquid (e.g., fish emulsion, seaweed extract) forms, each providing specific nutrients essential for plant growth. Notably, many of these products are byproducts of various industries such as fisheries, livestock, and food processing and can help in establishing a circular economy [10].

The Organic Materials Review Institute (OMRI) assesses products for compliance with the USDA's National Organic Program (NOP). As of 2023, 4101 OMRI-listed products fall under the category of Crop Fertilizers and Soil Amendments across 190 different product categories. Organic fertilizers are rich in macronutrients, micronutrients, and growth-promoting substances. Their addition to soil not only nourishes plants but also improves nutrient cycling [11]. Nonetheless, there is a noticeable gap in farmers' understanding of these products, encompassing aspects like their selection, cost, availability, scalability, and, to a certain extent, the anticipated impact on crop yield.

This paper aims to provide a comprehensive overview of the organic farming system, including its development and challenges, and a detailed examination of organic fertilizer sources commonly used in crop production. This study also explores the properties and categorization of commercially available organic fertilizers, considering those listed by the OMRI and their certification or approval process. The discussion incorporates research insights on vegetable crop performance and addresses the current challenges and future recommendations. This paper also adds the author's perspective on organic farming and its broader implications.

2. Overview of Organic Farming

2.1. Historical Development

Organic farming, which is often perceived as a contemporary movement, possesses historical roots deeply embedded in ancient agricultural practices. Before the 20th century's agricultural revolution, many farming methodologies inherently aligned with what we understand as "organic" today. Traditional agricultural practices naturally adhered to organic methods since synthetic chemicals and genetically modified organisms (GMOs) had not been developed [12]. However, the scene shifted dramatically with the advent of the Industrial Revolution and the Green Revolution in the 20th century. The introduction of synthetic fertilizers, pesticides, and modern mechanization marked a significant departure from these age-old practices [13].

By the 1920s and 1950s, concerns were rising regarding the excessive industrialization of agriculture. Visionaries like Sir Albert Howard, Lady Eve Balfour, and J.I. Rodale began championing a return to more natural farming methods [14–16]. Their pioneering work laid the groundwork for the modern organic movement, underscoring the importance of soil health, the virtues of natural pest control, and the potential perils of synthetic chemicals.

In the following years, especially during the 1960s and 1970s, there was a growing awareness of environmental issues. This was, in part, propelled by seminal publications like Rachel Carson's "*Silent Spring*" [17]. *Silent Spring* highlights the environmental and health effects of pesticides and symbolizes a distant future spring, where there will be no birds' songs. Following this, the era observed the establishment of the first formal organic certification systems and the rise of organic farming associations [18]. Organic farming transitioned from traditional practices to being recognized as a viable, sustainable alternative to conventional farming [18].

As we approached the late 20th century and early 21st century, organic farming began gaining acceptance in mainstream society. The health and ecological benefits of organic produce started gaining broader acknowledgment [19]. In 2002, a pivotal development took place when the USDA rolled out the National Organic Program (NOP), instituting federal standards for organic production in the United States. This trend was not limited to the United States; numerous other nations rolled out similar national guidelines during this period [20]. For example, five national organizations, including the Rodale Institute, came together to form an international organization in 1972, known as the International Federation of Organic Agriculture Movements (IFOAM), to coordinate their actions as well as to enable scientific and experimental data on organic to cross borders [21].

On the global stage, organic farming witnessed exponential growth, with countries like India and China and numerous African nations recording substantial upticks [22]. The organic market evolved, diversifying its offerings, which now span from staple produce to processed foods, textiles, cosmetics, and beyond. As the global trade of organic products intensified, discussions about harmonizing organic regulations between countries took center stage [21].

Nevertheless, organic farming is not without its challenges and critiques. As the organic sector flourished, it struggled with issues related to scalability, certification, and upholding the ethos of organic integrity [23]. Looking forward, there is a noticeable transition towards "beyond organic" or "regenerative" agricultural practices. These methods not only avoid synthetic inputs but also actively champion soil health, biodiversity, and holistic ecosystem rejuvenation [24]. As challenges like climate change and global food security, the merits of organic and sustainable farming practices are becoming more apparent [25]. Regenerative organic farming is a holistic approach. A 40-year period long-term Farming Systems Trial (FST) conducted by Rodale Institute has shown how regenerative organic agriculture outperforms conventional grain cropping systems during times of extreme weather, where corn yield was 31% higher in organic than in conventional during droughts [26].

Over the past century, organic farming has metamorphosed from a niche movement to a global industry. Despite facing its share of challenges and critiques, its foundational principles—environmental well-being, sustainability, and natural production—continue to wield influence and are progressively shaping the discourse on the future of agriculture [27].

2.2. Trends in Development

Over the past two decades, there has been a marked rise in the number of organic farms and land under organic cultivation (Figure 1). This trend is evident globally, from North America to Europe to Asia. For instance, in the United States, organic food sales have witnessed consistent growth, with organic fruits and vegetables sharing a significant market share. Similarly, European countries like Germany and France have seen an uptick in organic agricultural practices and consumer demand [28].

Regions in Australia and parts of Asia are also embracing organic agriculture, driven by both production and consumption incentives. This global inclination towards organic farming stems from a confluence of factors, including heightened consumer awareness about food safety and health, concerns over environmental impacts, and the long-term economic promise of organic farming. According to a recent report published by IFOAM and FiBL, there were more than 74.9 million hectares of organic farmland globally in 2019, which is 1.6% of the total farmland [29], and which increased to 76.4 in 2021 (Figure 1). Trend analysis with data from 1999 to 2021 showed a gradual increase in the sales of organic food and the area of acreage under organic farming, with an annual increase of USD 5 billion in sales and an annual increase of 2.9 million hectares of land dedicated to organic farming each year (Figure 1). Worldwide, 191 countries practice organic agriculture with 2.8 million organic producers, and 1.6% of the world's agricultural land is farmed organically. In the USA, there was a 36% increase in certified organic farms between 2015 and 2021 [30].

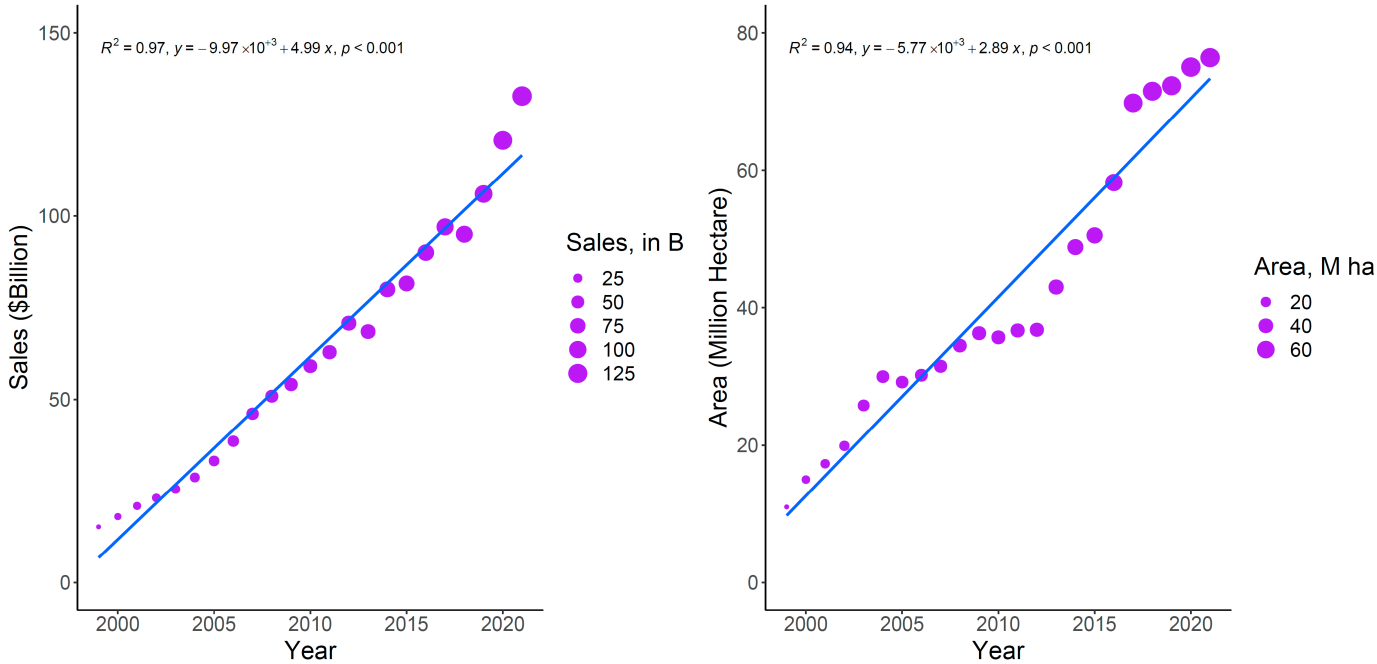

Figure 1. Global trends (linear regression) in organic food sales and the total area of acreage increase from 1999 to 2021. Here, sales are represented as billions in USD (B) and area is represented as millions of hectares (M ha). The coefficient of determination (R^2), regression equation (y), and *p*-value are indicated. Data source: Statista, 2023; Willer and Lernoud, 2019 [29,31].

2.3. Benefits of Organic Farming

2.3.1. Environmental Benefits

Organic farming, with its foundation in ecologically balanced agricultural principles, presents a myriad of environmental benefits. By avoiding synthetic fertilizers and pesticides, organic farms significantly reduce the likelihood of groundwater contamination. For instance, a comprehensive study in Europe found that areas with intensive organic farming had 40% less nitrate in groundwater compared to conventional farming regions [32]. Organically managed soils show a higher water-holding capacity and infiltration rate due to their higher organic matter content [33,34]. Furthermore, by prioritizing soil health through practices like crop rotation and green manuring, organic farming not only augments soil fertility but also improves biodiversity. A meta-analysis revealed that organic farms, on average, support more plant, insect, and animal species than conventional farms [35]. Such practices also play a pivotal role in attenuating soil erosion, with some estimates suggesting that soil erosion potential can be reduced by over 61% with organic practices [36,37]. Land management with organic manure can increase soil organic matter [38]. Agriculture is a major contributor to climate change, emitting around 22% of global anthropogenic greenhouse gas (GHG). Organic management has shown reductions in total GHG emissions per unit area [3].

2.3.2. Economic Benefits

While facing the initial financial challenges remains in transitioning to organic farming, the long-term economic prospects are promising. Organic products consistently command premium prices often between 20 and 30% higher than their conventional counterparts. By eliminating the recurring costs associated with synthetic fertilizers and pesticides, organic farms can also achieve substantial savings eventually. Furthermore, the "organic" label offers a competitive edge in the market. For example, the global organic food market size was valued at approximately USD 208.2 billion in 2022 and is expected to grow at a compound annual growth rate (CAGR) of 11.7% from 2023 to 2030 [39]. Organic systems also have higher socio-ecological resilience than conventional systems owing to its diverse mixed farming approach, which can minimize risk by reducing the economic dependence on a single crop [3].

2.3.3. Health Benefits

Organic foods, which are produced devoid of synthetic pesticides and genetically modified organisms, cater to the escalating consumer inclination for natural and uncontaminated foods. Research has indicated that organic crops, on average, have higher concentrations of antioxidants, lower levels of cadmium (Cd), and a reduced frequency of pesticide residues compared to conventionally grown crops [40]. For instance, organic tomatoes were found to contain, on average, more vitamin C than conventional tomatoes [41]. By reducing the application of synthetic chemicals, organic farming also minimizes the potential health risks posed by pesticide residues. This approach has potential to decrease the incidence of certain chronic diseases and conditions [42].

3. Challenges in Organic Farming

Organic farming, while offering numerous advantages in terms of sustainability, environmental conservation, and health benefits, confronts a myriad of challenges that can impact its efficacy and adoption rate. This section explores the multifaceted challenges experienced by practitioners of organic farming, explaining both the inherent complexities of the method and the external factors that influence its application.

3.1. Organic Nutrient Sourcing

One of the primary challenges in organic farming is the sourcing and application of organic nutrients. Unlike conventional agriculture, which has access to a wide range of synthetic fertilizers designed to meet specific nutrient requirements, organic farmers have a narrower spectrum of choices. These organic inputs, such as compost, manure, and bone meal, can vary considerably in nutrient content/imbalance amount of nutrients as needed by plants, demanding careful management to ensure balanced soil fertility [43]. In addition, the availability of organic fertilizers in the market is another concern. It is required in bulk quantity due to its lower nutrient concentration compared to synthetic fertilizers and can be associated with transporting and handling challenges [44].

3.2. Pest and Pathogen Management

The non-reliance on synthetic pesticides and herbicides in organic farming reintroduces the challenge of managing insect pests, weeds, and pathogens. Moreover, the variability in environmental conditions and pest behaviors adds complexity to this scenario. The organic approach demands a more intricate strategy, encompassing crop rotation, companion planting, biological controls, and tillage to some extent. While these methods can be effective, they often require a more nuanced understanding and can sometimes be less predictable in outcome compared to chemical controls [45].

3.3. Soil and Crop Management

Managing soil fertility in organic farming can be quite challenging, particularly when it comes to the use of organic fertilizers. Unlike inorganic fertilizers, organic fertilizers contain fewer nutrients and do not have a targeted source of nutrients. Instead, they are a blend of several nutrients available in organic form, which need to be mineralized to release the nutrients for plant uptake. As a result, it can be difficult to manage the required and recommended nutrient levels, especially for high nutrient-demanding crops [46]. This would be more critical when growers produce longer-growing season greenhouse crops like cucumber, tomato, and sweet pepper. These crops demand a continuous and consistent supply of nutrients throughout the growth stages [47,48]. The asynchronous release of nutrients in organic farming can pose challenges in meeting crop demand and can also be a cause of environmental pollution.

3.4. Yield Gap and Economic and Logistic Concerns

Organic farming, despite its environmental and health benefits, frequently faces a persistent challenge of lower yields compared to conventional farming, known as the "yield gap". Studies show that, on average, organic crop yields in developed nations are between 5% to 34% lower than their conventional counterparts [49,50]. This is attributed to organic farming's reliance on the natural decomposition of organic fertilizers, like compost, to release nutrients [43]. Unlike conventional farming using synthetic fertilizers, organic farming lacks flexibility in adjusting nutrient availability in response to crop needs, leading to lower yields.

Moreover, the absence of synthetic herbicides in organic farming requires labor-intensive manual or mechanical weed removal, which may fail to control aggressive weed species and incur additional costs [51]. Transitioning to organic farming can pose significant economic challenges, involving expenses for organic certification, infrastructure modifications, and the potential for reduced yields during the transition phase, which can strain financial resources. Additionally, the logistical challenges of sourcing organic seeds and managing extended crop rotations further add hurdles for farmers [52]. A notable example is Sri Lanka. In 2021, the country banned the import and use of synthetic fertilizers and pesticides without adequate support for farmers and consumers. This led to a drastic 30–50% decrease in crop yields, forcing many farmers to abandon their fields, skyrocketing food prices, and necessitating the importation of rice worth hundreds of millions of dollars. Sri Lanka, once a self-sufficient producer of rice, faced significant challenges. This highlights that the shift to organic agriculture must be carefully planned and tailored to local resources and capabilities.

3.5. Knowledge and Training

The principles of organic farming have ancient roots, face challenges in their application in contemporary settings, and often require specialized knowledge and training. For example, the benefits of adopting cover crop practices are more for improving soil health and structure than increasing farm profitability. Similarly, research results obtained in one zone (e.g., temperate) cannot be readily transferred to another zone, which requires a better system understanding of tropical, sub-tropical, and arid climates. Access to training, research, and extension services tailored to organic farming can be limited in many regions, hindering the adoption and optimization of organic practices [53].

4. Organic Fertilizers: Categories and Characterization

4.1. Major Classification

Organic production systems offer diverse nutrient sources, including compost, manure, green manure, meals, biosolids, mineral fertilizers, and microbial solutions. We have categorized the organic fertilizers into six distinct groups based on their source, which are also summarized in Table 1:

1. **Animal-based fertilizers:** manure, bone meal, blood meal, fish emulsion, and feather meal;
2. **Plant-based fertilizers:** compost, green manure, cottonseed meal, and seaweed extracts;
3. **Mineral-based fertilizers:** rock phosphate, greensand, and lime;
4. **Specialty organic fertilizer:** bat guano, worm casting (vermicasting), and biochar;
5. **Microbial inoculants:** mycorrhizae and bacterial inoculants;
6. **Wastewater-derived organic fertilizer:** biosolids.

Table 1. Comprehensive overview of organic fertilizer types: analyzing benefits, challenges, nutrient profiles, environmental impact, suitable crops, and shelf life.

Category	Benefits	Challenges	As Major Nutrient Source	Environmental Impact	Suitable Crops	Shelf Life	References
Animal-Based Fertilizers	High nutrient content; improves soil structure and water retention	Risk of pathogenic contamination; odor and potential nutrient loss via runoff and leaching	i. N (from manure, blood meal) ii. P and Ca (from bone meal) iii. N-P-K (from fish emulsion)	Medium to high; potential water pollution from runoff and leaching and pathogenic contamination; greenhouse gas emissions and odors; phosphorus leaching from long-term manure application.	Most crops	Several weeks to months	[54–61]
Plant-Based Fertilizers	Renewable and eco-friendly; enhances soil microbial activity	Slower nutrient release; potentially lower nutrient content than animal-based fertilizers	i. N (from green manure) ii. Minor trace elements (from seaweed extracts) iii. Balanced nutrients (from compost)	Low; contributes to soil health with minimal negative impact; composting reduces landfill waste and methane emissions; sustainable harvesting of seaweed is crucial to minimize ecosystem disruption.	A broad range of crops, including root vegetables, leafy greens, and herbs	Varies; compost is stable	[62–65]
Mineral-Based Fertilizers	Natural and eco-friendly; slow release ensures prolonged nutrient availability	Variable nutrient content; may require additional processing	i. P (from rock phosphate) ii. K (from greensand) iii. Ca (from lime)	Medium: mining of rock phosphate and greensand can lead to land degradation and habitat disruption; lime application must be managed to prevent soil alkalinity imbalance.	Suitable for crops requiring specific nutrients like beans (P) and potatoes (K)	4–6 weeks or longer	[66,67]
Specialty Organic Fertilizers	Unique nutrient compositions; specific benefits like high N content or soil improvement	Availability and cost; specific handling requirements	i. High N (from bat guano) ii. N, P, K, Zn, and beneficial microbes (from worm castings) iii. C-rich material (from biochar)	Generally low to moderate; sourcing of bat guano needs to be sustainable to avoid ecological disruption; biochar production has a positive impact on carbon sequestration (longer persistence of biochar than the biomass it is made from).	Specific to needs, e.g., high-demand crops for bat guano e.g., okra, tomato, lettuce, kale	Varies significantly	[68,69]
Microbial Inoculants	Enhances nutrient uptake and soil health; supports plant growth	Requires specific soil and environmental conditions for effectiveness; application expertise needed	Beneficial microbes, no direct N-P-K content; phyto-stimulatory	Low; enhances soil biodiversity and health without negative impacts; can reduce the need for chemical fertilizers, thereby lowering environmental stress.	Broadly applicable (vegetables to row crops), especially beneficial for crops sensitive to soil conditions	1–2 years or more	[70,71]

Table 1. *Cont.*

Category	Benefits	Challenges	As Major Nutrient Source	Environmental Impact	Suitable Crops	Shelf Life	References
Wastewater-Derived Organic Fertilizer (Biosolids)	Higher nutrient in balanced composition; improves soil health, water retention, soil structure, and crop yield	Risk of pathogenic contamination; heavy metal contamination; potential source of toxic pharmaceutical and personal care products (e.g., Triclosan), endocrine-disrupting compounds (Bisphenol A), and dioxins and furans	Nutrients: N, P, K, S, Mg, Ca, Zn, Cu, and B; Biosolids can also contain heavy metals such as As, Hg, Se, Cr, and Ni	Possibilities of water pollution and soil contamination when applied long term and exceed the recommended rates; nutrient leaching; eutrophication, and negatively impacting aquatic ecosystems; health risks due to the presence of endocrine-disrupting compounds and dioxin and furans.	Most crops; can be used for row crops like corn, wheat, and soybean	1–2 years	[72–74]

Note: Fertilizers are classified into high, moderate, and low categories based on their effectiveness.

4.2. Organic Fertilizer: Nutrient Profile, Application, and Challenges

In exploring the use of organic fertilizer, it is important to recognize that managing nutrient budgets with organic sources can be challenging. This challenge arises from their low nutrient profile, variability in mineralization dynamics, and complex organic compositions. Additionally, there are challenges in their production, outsourcing, shelf life, and environmental implications. This section covers the most commonly available and used organic nutrient sources and discusses their nutrient profile, application, and challenges. Specific information on the nutritional composition of organic fertilizers is provided in Table 2.

Table 2. Nutrient composition of various organic fertilizers and soil amendments.

Material	% Nitrogen	% Phosphate	% Potash
Alfalfa hay	2–3	0.5–1	1–2
Bone meal	1–6	11–30	0
Blood meal	12	1–2	0–1
Cottonseed meal	6	3	1
Composts	1–3	1–2	1–2
Feather meal	12	0	0
Fish meal	6–12	3–7	2–5
Grass clippings	1–2	0–0.5	1–2
Hoof/horn meal	12–14	1.5–2	0
Kelp	1–1.5	0.5–1	5–10
Leaves	1	0–0.5	0–0.5
Legumes	2–4	0–0.5	2–3
Manures: cattle	2–3	0.5–1	1–2
Horse	1–2	0.5–1	1–2
Swine	2–3	0.5–1	1–2
Poultry	3–4	1–2	1–2
Sheep	3–4	0.5–1	2–3
Pine needles	0.5	0	1
Sawdust	0–1	0–0.5	0–1
Sewage sludge	2–6	1–4	0–1
Seaweed extract	1	2	5
Straw/corn stalks	0–0.5	0–0.5	1
Wood ashes	0	1–2	3–7

Adopted from Utah State University, Yard and Garden Extension [75], written by R. Koenig and M. Johnson, received permission from authors to re-use.

4.2.1. Animal-Based Fertilizers

A. Manure

Manure, a natural fertilizer consisting of animal feces and urine mixed with hay or straw, is a key component of organic farming, providing numerous benefits to soil and crops. This can be broadly categorized into cow, horse, sheep, chicken, pig, goat, and rabbit manure, each with varying nutrient contents (NPK and other nutrient values). For instance, cow manure typically contains N concentrations ranging from 0.5% to 3%, P concentrations ranging from 0.3% to 0.6%, and K concentrations ranging from 0.5% to 3%. Chicken manure is particularly rich in nutrients, with N ranging from 1.5% to 3.5%, P from 1.5% to 3%, and K from 0.8% to 2.5%. Factors like animals' diet, manure's age, and storage influence nutrient concentrations. Fresh manure has lower nutrient concentrations than composted or aged manure due to higher water content. Hence, manure analysis is recommended for precise nutrient management. While long-term manure application enhances crop yield and improves soil organic matter and health [38,54,76], challenges like the overaccumulation of P nutrient exist, which can cause eutrophication [38,54,55,77]. Excessive application can also cause issues like salinity and acidity [78]. Manure has also been reported as a source of greenhouse gas emissions, especially methane and nitrous oxide [58]. Manure is often composted before application to reduce the pathogenic risk and weed emergence count. Proper manure management incurs costs, and obtaining a large amount of manure can also be a challenge depending on location.

B. Blood Meal

Blood meal, a popular organic fertilizer derived from dried and ground animal blood, is a cost-effective and efficient source of N for plants, particularly high-N-demanding vegetables such as lettuce, spinach, kale, tomatoes, peppers, cucumbers, and okra. Despite its high N content (10–13%) compared to other organic sources, it is also a slow-release fertilizer. Blood meal is mainly composed of hemoglobin (globular protein) and is characterized by the presence of a prosthetic group (protoporphyrin) containing iron (Fe) [60]. Limited information exists on its role as an Fe source for plants [61,79]. Excessive application of blood meal can lead to a high concentration of N, potentially burning the plant by disrupting its water uptake system. The strong smell of blood meal can attract animals and pests like dogs, rodents, and raccoons, which may dig up gardens or plant beds where it is applied. Overapplication may lower the soil pH, making it more acidic. While rich in N, blood meal lacks P and K. Safety precautions are advised during handling as a slaughterhouse byproduct, though disease transmission risk is low.

C. Bone Meal

Bone meal, a popular organic fertilizer derived from finely ground animal bones, is rich in P (15–27%) and Ca (22–33%) [80]. Bone meal also contains a small amount of N (1–4%) and trace minerals, including collagens. Bone meals, while beneficial in many contexts, are not universally applicable. It may not be ideal for plants that demand substantial amounts of N or for use in soils with high acidity. The reason lies in bone meal's slow transformation into soluble P in acidic conditions. This characteristic can be advantageous in P-deficient soils, aiding plant growth. However, in soils that already have sufficient phosphorus, bone meal tends to convert into a stable form of phosphorus, offering no additional benefits to the plants. Excessive use can lead to a build-up of phosphorus in the soil, which can disrupt the balance of soil nutrients and potentially lead to environmental problems like water pollution. Variability in nutrient content, attractiveness to pests, and impact on soil pH make bone meal less consistent in its effectiveness as a fertilizer.

D. Fish Emulsion

Fish meal, comprising fish and seaweed emulsions and meals, is an organic nutrient source with a relatively high level of N (10%) and P (6%) [81,82]. While its rapid mineralization is advantageous [81], its unpleasant odor in closed environments like greenhouses can be a drawback. At typical summer soil temperatures, more than half of the organic N may mineralize within two weeks of application. However, overapplication of fish emulsion can cause N burn, harming plant roots and leaves. The nutrient profile varies based on source and manufacturing processes, leading to inconsistent results. The biggest challenge for fish emulsion is its shelf life, and improper storage can reduce efficacy. The fish emulsion generally needs to be diluted before application, which increases the additional preparation time. Depending upon the brand and quality, fish emulsion can be more expensive than some other organic fertilizers.

E. Feather Meal

Feather meal, a poultry industry byproduct, contains relatively high N levels (14%). Although initially insoluble, it mineralizes rapidly (around 2 weeks) under favorable conditions. In soil, where the substrate is not limited to a short retention period, the prolonged decomposition of a protein-rich material may be advantageous [83]. Feather meal is the least expensive organic fertilizer, but its effectiveness depends on soil microbial activity, varying with soil type, pH, and other conditions. Some processing methods for converting feathers into meal involve chemicals or high heat, which can raise additional environmental concerns. Application and storage pose challenges; feather meal can be dusty and inhaling it can be unpleasant or potentially harmful. Improver storage can reduce the effectiveness of feather meal.

4.2.2. Plant-Based Fertilizers

A. Compost

Compost, a key element in sustainable waste management, results from the aerobic decomposition of organic matter like kitchen scraps, yard waste, and agricultural residues. It enhances soil structure, water retention, and microbial activity [84–86]. Composting can be categorized into various types based on the method and materials used, including home composting, vermicomposting (using earthworms to accelerate decomposition) [87], bokashi (a method involving fermentation) [88], and large-scale industrial composting. Benefits encompass the enrichment of essential nutrients, improvement in soil aeration and moisture retention, aiding carbon sequestration, and reducing greenhouse gas emissions by diverting organic waste from landfills. Challenges involve space and maintenance in home composting, specific conditions for vermicomposting, an anaerobic environment for bokashi composting [89]. Large-scale composting facilities are challenged by the need for significant infrastructure, regulatory compliance, and potential odor and leachate management issues. Moreover, compost quality varies based on the inputs and processes, impacting its suitability for different applications. In all forms, composting necessitates a balance between N-rich and C-rich materials to ensure effective decomposition, a factor that requires careful attention to detail. Despite challenges, the continued innovation and adaptation holds potential for enhancing its efficacy and applicability in diverse settings.

B. Green Manure

Green manure, involving fresh plant material incorporation, especially from fast-growing cover crops, offers a sustainable approach to enhancing soil quality/health. Crops like legumes such as clover, vetch, and peas, as well as grasses such as rye and barley, are sown not for harvest but for their beneficial impact on soil health [90–92]. Their integration into farming systems notably contributes to N fixation and the improvement in soil structure and organic matter content. However, the implementation of green manure is not without its challenges, for example, precise timing and management; the growth period of these crops can sometimes conflict with the scheduling of main crop planting. Additionally, the incorporation of green manure into the soil must be meticulously timed to occur before the plants reach seeding stage. This process, while beneficial for soil health, can be labor-intensive and necessitates appropriate agricultural equipment. Moreover, water resource management emerges as a crucial consideration, especially in arid conditions where supplementary irrigation might be required [63]. In addition, it can attract pests and diseases that carry over to subsequent crops and potentially lead to temporal N depletion in soil. Furthermore, species selection, climatic conditions, and decomposition rate of these crops can impact on achieving desired outcomes. While green manure presents an ecologically sound method for improving soil health, its integration into agricultural systems demands careful planning and resource management to optimize its benefits and mitigate potential drawbacks.

C. Cottonseed Meal

Cottonseed meal, an organic fertilizer derived from cotton seed byproducts, is rich in N (6–7%), P (1–3%), and K (1.5%). It is particularly known for enhancing vegetative growth and root development, while its slow-release property ensures a prolonged nutrient supply, minimizing over-fertilization risks. Additionally, its acidifying effect on soil renders it ideal for acid-loving plants, making it a versatile choice for a variety of garden settings. Challenges include its specific nutrient ratio not fitting for all plants or soil types, potential residual chemicals, the allergenic properties of cottonseed (a known allergen which may pose risks during handling) [93], pest attraction, variable availability, and cost effectiveness. Applied in spring as a side dressing or soil mix, cottonseed meal recognized as beneficial for plants that thrive in slightly acidic soils, such as azaleas, blueberries, and rhododendrons [94], offering sustainable and environmentally friendly fertilization. However, careful consideration is essential for tailored application and to address potential challenges.

D. Seaweed Extracts (Kelp Meal)

Kelp meal, which is derived from kelp or brown algae seaweed, is nutrient-rich in fertilizer containing N, P, K, and various trace elements. Marketed as biostimulants, fertilizers, soil conditioners, and environmental stress reducers [95], it offers benefits but faces challenges such as variability in nutrient content and production costs, and there is still a lack of information regarding the effectiveness of kelp meal products in different agroecosystems and specialty crops. Contamination is another concern, as seaweed can accumulate heavy metals from the marine environment and issues with stability and shelf life require careful handling. Despite these hurdles, seaweed extract remains a valuable component in organic farming, contributing to plant health and sustainable practices when used in conjunction with other organic fertilizers.

E. Alfalfa Meal

Alfalfa meal, an organic fertilizer from ground alfalfa plants, rich in N (2–3%), P, and K, promotes healthy growth in diverse plants. It also contains essential trace minerals, improving soil structure and moisture retention. While its N level may not meet the needs of high-demand crops and it can also attract pests, combining it with other fertilizers ensures comprehensive plant nutrition. Its applicability extends to gardening and farming, offering a sustainable choice for enriching soil.

4.2.3. Mineral-Based Fertilizers

A. Rock Phosphate

Rock phosphate fertilizer, an organic fertilizer, originates from phosphorite or rock phosphate, a sedimentary rock containing high amounts of phosphate minerals. It is mined in countries like Morocco, China, and the United States. Its composition primarily includes P in the form of phosphates, and it may also contain beneficial minerals like Ca and Fe, along with trace elements essential for plant growth. In organic farming, rock phosphate is utilized as a soil amendment and a slow-release phosphorus fertilizer. Typically applied directly to soil, it plays a crucial role in supporting root development and flowering in a variety of plants, including vegetables, fruits, and ornamentals. Additionally, it improves soil health by enhancing soil structure and water retention capabilities and is considered more environmentally friendly compared to synthetic P fertilizers. Despite these advantages, there are challenges associated with rock phosphate fertilizer, for example, slow nutrient release and variable effectiveness due to composition and soil conditions. Moreover, the mining of rock phosphate raises environmental concerns; therefore, its use should be carefully considered based on the specific needs of the soil and crops.

B. Greensand

Greensand, a natural mineral with a distinctive green hue from iron silicate compounds, is a valuable resource in gardening and agriculture. Extracted from ancient seabed deposits, it primarily consists of glauconite, an iron potassium silicate mineral, and trace minerals. Greensand is known for its slow-release K content, being vital for plant health, photosynthesis, and nutrient absorption; it also improves soil structure and water retention. It is particularly beneficial for sandy soils and can also loosen clay soils, promoting root growth. One of the key advantages of greensand is its ability to release nutrients gradually, preventing the risks associated with over-fertilization and offering a sustainable solution for long-term nutrient provision. As a natural soil conditioner, it improves texture and essential trace minerals that might be missing in some soils. Being a natural and organic product, greensand is a favored choice in organic gardening, devoid of synthetic chemicals. Greensand is typically applied directly to soil; its rates can vary based on soil type and plant needs. While effective for slow-release and soil conditioning, it may not rapidly correct severe nutrient deficiencies and works best in slightly acidic to neutral pH soils.

C. Lime

Lime, a crucial soil amendment in gardening and agriculture, is derived from ground limestone rock, which is primarily composed of calcium carbonate ($CaCO_3$) and, in some types, magnesium carbonate ($MgCO_3$). Two main types, calcitic lime and dolomitic lime, serve to raise the soil pH of acidic soils, which is essential for plants that thrive in neutral to alkaline conditions. Lime improves nutrient availability, particularly P and K, and improves soil structure by aiding water retention and aeration. This amendment is indispensable for providing plants with essential nutrients like Ca and Mg, which are crucial for growth and development and are applied before planting. Conducting a soil test before application is crucial to determining the necessary amount of lime, as its overuse can lead to an overly alkaline soil environment, adversely affecting plant growth and nutrient absorption. It is also important to note that lime reacts slowly with soil; therefore, it should be applied well in advance of planting. While not a substitute for fertilizers, lime is integral to comprehensive soil management, ensuring optimal conditions for a variety of plants, particularly those unsuited for acidic soils.

4.2.4. Specialty Organic Fertilizer

A. Bat Guano

Bat guano, the excrement of bats, is a highly recognized organic fertilizer known for its rich nutrient content, especially N, and beneficial impact on soil and plants. High in N for leafy plant growth, it also provides P for root development, K for overall plant health, and beneficial microorganisms and trace elements, contributing to soil health and improving plant resilience against diseases. Its standout feature is fast-acting nutrient release, offering a quick boost in growth. It is versatile in its application and suited for various gardens and plants, acting as both fertilizer and soil conditioner, enhancing structure, moisture retention, and microbial activity. Despite its benefits, careful use is crucial to avoid nutrient imbalances, making it an integral part of a balanced fertilization strategy aligned with plant and soil needs.

B. Worm Casting (Vermicasting)

Worm castings, or vermicasting, are potent organic fertilizers created through earthworm digestion, offering a rich array of essential nutrients and enhancing soil properties. With balanced levels of N (1–2%), P (1–2%), and K (0.5–1%), along with micronutrients, they support comprehensive plant growth. One of the standout features of worm castings is their high concentration of beneficial microorganisms, which play a crucial role in breaking down nutrients and improving soil structure [96]. They also contain humic acid, enhancing nutrient absorption and increasing soil water retention. The exact nutrient composition can vary based on the worms' diet and the production conditions of the vermicasting. In terms of application, worm castings improve soil aeration and water retention due to their porous nature and are pH-neutral, making them suitable for a wide range of plants and soil types. They can be mixed into garden beds, added to potting mixes, and used as a top dressing. Despite being pH-neutral and versatile, challenges in their use include their cost, nutrient variability, production demands, and lower concentrations compared to synthetic fertilizers. Proper storage is crucial to maintain effectiveness, and overapplication may lead to nutrient imbalances and pest attraction. While research is limited, worm castings remain invaluable for sustainable and organic gardening, contributing significantly to long-term soil health and plant growth when integrated into a balanced soil management and fertilization strategy.

C. Biochar

Biochar, a carbon-rich product derived from the thermal decomposition of organic materials in an oxygen-limited condition, is a vital soil amendment in organic farming. Its rich porous structure enhances water and nutrient retention, promoting soil health and crop productivity. When used directly in soil or during composting, biochar improves soil structure, aeration, soil organic matter, and water infiltration [97,98]. Its nutrient retention reduces reliance on chemical fertilizers, aligning with organic principles. Additionally, biochar's stability in soil makes it an effective means of carbon sequestration and allows it to reduce greenhouse gas emissions [69]. This, in turn, contributes to improved plant growth and yield. Challenges include production and transportation costs, variable effectiveness due to differences in quality, and a lack of long-term research on diverse soil types and ecosystems. Careful consideration and ongoing study are essential for maximizing biochar's benefits in organic farming.

4.2.5. Wastewater-Derived Organic Fertilizer

Biosolids

Biosolids, which are derived from wastewater treatment processes, are treated sewage sludge used in agriculture and landscaping. There are different kinds of biosolids, categorized based on their treatment and pollutant levels: Class A biosolids are highly treated and contain minimal pathogens, making them safe for public use, while Class B biosolids have undergone less treatment and may have restrictions on their application. While beneficial for soil due to the presence of organic matter and essential nutrients (N, P, and trace minerals), their use in organic farming faces scrutiny due to concerns about contaminants such as heavy metals and pharmaceuticals. Challenges include public perception, regulatory constraints, and variable composition. Despite existing challenges, research is ongoing to enhance treatment processes and assess long-term impacts, highlighting biosolids as a potential resource for soil health and crop production.

4.3. Ecosystem Services of Organic Fertilizers

The pivotal role of organic fertilizers in fostering ecosystem services for crop production is evident. Those can include enhancing biodiversity, nutrient cycling, soil health, and farm productivity. Further insights into the economic, environmental, soil health, and crop yield impact of different organic fertilizers in crop production are detailed in Table 3.

Table 3. The economics, soil health, and environmental impact of organic fertilizers in crop production.

Fertilizer Type	Initial Cost (per Unit)	Yield Impact	Soil Health Impact	Environmental Impact	References
Manure	USD 15–28 per ton	Long-term manure application improves crop yield (most of the crops and vegetables).	Improves soil organic matter, soil organic carbon, water retention, soil microbial biomass.	Long-term application of manure has the potential to cause water contamination and phosphorus leaching.	[38,76]
Greensand	USD 33 per 50 lbs	Availability is limited to a few garden studies found on independent websites. It is primarily used as a soil conditioner for flower beds, gardens, and lawns.	It improves water retention and microbial growth, promotes plant root growth by loosening clay soil, and helps bind sandy soil.	None to report due to limited studies.	[66,99]
Rock Phosphate	USD 35 per 50 lbs	It improves crop yield but varies based on soil types and nutrient profiles.	Improve carbon sequestration and accumulation by increasing soil exchangeable calcium and magnesium cations.	Overapplication of rock phosphate can lead to water pollution and accumulation of cadmium, which is harmful to the environment.	[100,101]
Lime	USD 12 per 50 lbs	Liming can significantly enhance the effectiveness of fertilizers by reducing soil acidity, potentially leading to yield increases of 20% or more in crops such as corn and soybean. For alfalfa, the yield improvement can be 35% or greater.	Liming increases soil pH, which stimulates microbial activity and enhances soil organic matter. This process can significantly impact the dynamics of carbon pools in the soil. By lowering soil acidity, liming not only improves crop yield but also enhances the soil's water retention capacity.	Over-liming can add excess calcium, which can lead to deficiencies in nutrients like magnesium and potassium.	[102–106]
Bone Meal	USD 40 per 50 lbs	Improves protein content in spring and winter wheat; crude fat yield in rapeseed; and yield in sweet corn and perennial grass.	Increases soil pH and improves total and mineral nitrogen, total phosphorus, and dissolved organic carbon.	Reduces the bioavailability of lead, zinc, and cadmium in polluted soils.	[107–111]
Blood Meal	USD 60–100 per 50 lbs	Reduce chemical fertilizer dependency for cereals, oilseed rape, and sweet corn; contradictory, one study also reported a potential inhibitory effect on maize establishment.	Increases soil organic matter and fertility; improves the availability of iron and micronutrients for plant growth and development.	Potential risk of water contamination and heavy metal pollution.	[60,61]

Table 3. *Cont.*

Fertilizer Type	Initial Cost (per Unit)	Yield Impact	Soil Health Impact	Environmental Impact	References
Fish Emulsion	USD 20 per gallon	Improves crop yield in tomato and rice.	Positive impact on disease suppression and plant growth.	Fish can accumulate heavy metals in their marine environment, which can then be transferred to soil and plants; high nitrogen content can lead to nutrient runoff if overapplied.	[112–115]
Seaweed Extracts	USD 25 per quart	Improves yield in tomato.	Improving soil nitrogen, soil fertility, and microbial activity enhances plant growth and yield; additionally, it improves water retention and nutrient uptake and provides plants with resistance to both abiotic and biotic stress environments.	Unsustainable harvesting of seaweed can disrupt marine ecosystems and biodiversity; the production and processing of seaweed extract may contribute to greenhouse gas emissions, depending on the method; the heavy metals accumulated by seaweed may get transferred to the soil.	[116–120]
Alfalfa Meal	USD 30–60 per 50 lbs	While there is a lack of specific scientific reports, several independent websites have dmonstrated that alfalfa meal contributes to an increase in organic matter, trace minerals, and NPK levels. Additionally, when used as mulch, alfalfa can help in weed reduction. It is also noteworthy that alfalfa contains triacontanol, a natural plant growth stimulator, which has been reported to enhance yield in vegetable crops.	Alfalfa meal enhances soil microbial biomass and nitrogen levels, decomposes quickly, and positively impacts soil tilth and water retention.	Producing alfalfa meal requires careful consideration of water and land usage, particularly in environments with water scarcity. Additionally, if the alfalfa is treated with pesticides, there is a potential risk of transferring residues to both the soil and the plants.	[121,122]
Biosolids	USD 50–125 per dry ton	Biosolids improve crop yield in winter wheat and corn	Improves soil organic carbon and potentially mineralizable nitrogen, soil organic matter, water retention capacity, and water infiltration rate.	Biosolids can contain heavy metals, pathogens, and residual pharmaceuticals, posing a risk to water quality and human health.	[123–128]

Note: costs of organic fertilizers (in the U.S. market in 2023) are adapted from 7SpringsFarm and Fertrell Co. Plant, Bainbridge, PA, USA; data were collected in October 2023.

5. Regulation and Certification in North America

In organic farming, growers are using natural and much safer fertilizer products compared to chemical alternatives. However, it is essential to ensure that these organic fertilizers meet strict organic standards. The Organic Materials Review Institute (OMRI) plays a crucial role in this process. The OMRI is an independent non-profit organization that was started in 1997 and is dedicated to reviewing and certifying products used in organic production and processing. It evaluates a wide range of inputs, including fertilizers, pest controls, and livestock health care products, to ensure they comply with organic standards. When companies apply for OMRI certification, their products undergo rigorous scrutiny against these standards. The OMRI's standards are based on the U.S. National Organic Program (NOP), the Canada Organic Regime (COR) standards, and the Mexican Organic Products Law (LPO) guidelines. The review and approval process generally takes several months. If a product meets the criteria, it becomes OMRI-Listed® and is included in the OMRI Products Lists©, providing assurance to organic farmers and consumers that it is genuinely organic and safe for both human consumption and the environment. Any products need to be renewed annually.

A comprehensive directory of approved organic products, known as the OMRI Products List, is readily accessible for download at https://www.omri.org/omri-lists (accessed on 22 November 2023). The OMRI provides an electronic search tool that simplifies the process for organic community members to select suitable products. This tool not only aids in decision making but also allows users to conveniently obtain OMRI certificates for each approved product, ensuring transparency and adherence to organic standards. Since organic goods are becoming popular day by day, organic growers want to be confident with the products they choose. Hence, the OMRI Products List is helpful both for growers and certifiers. Although it is not mandatory to be listed, being OMRI-Listed can provide a significant advantage. The importance of OMRI certification for organic growers and consumers includes authenticity of organic products, compliance with organic standards, consumer trust, environmental benefits, and health implications [129].

6. Evidence of Crop Performance with Commercially Available Organic Fertilizers in Vegetable Production

Compared to research reports on the use of manure and compost in greenhouses or fields, little research has been conducted evaluating other commercially available organic fertilizers. The impact of organic farming on vegetable yield has shown varied results. According to a report by Olle and Williams, about 59% of studies observed positive effects on yield from organic cultivation, while 29% reported a negative impact, and 12% found no significant influence. Notably, around 65% of the studies indicated that vegetables grown organically had a better nutritional value than those grown conventionally [130]. This highlights the mixed but often positive effects of organic cultivation on vegetables' yield and nutritional quality. For instance, Maltais-Landry et al. (2023) reported an increase in the marketable yield of cabbage when using processed fertilizers—including blood meal, bone meal, feather meal, and meat meal—compared to composted manure and control in a two-year experiment [62]. Similarly, a recent study that examined the individual and combined effects of *Tithonia diversifolia*, banana leaves, and poultry feather (PF) on tomato crops found that combinations like PF and Tithonia leaves significantly increased tomato yield and improved soil properties compared to individual applications or control treatments [131]. A recent meta-analysis by Gao et al. (2023), which reviewed 107 research papers, found that organic fertilizers originating from animals improved the yield of tomato production by 42.2% [132]. This was followed by plant-origin organic fertilizers (35.8%) and mixed animal-and-plant organic fertilizers (37.2%) compared to crops with no fertilizer application. This improvement was attributed to the higher N release rate in animal-origin fertilizers compared to other organic fertilizers [133,134]. Additionally, the use of commercial fish emulsion as a plant growth medium and nutrient source has shown promising results in enhancing radish growth by promoting nutrient availability and plant growth, especially in sandy soils [135].

A two-year study compared the influence of plant- and animal-based organic fertilizers on soil nutrient availability, yield, and phytochemical content of artichokes. It was found that the concentration of phytochemicals was higher in soil treated with alfalfa meal than in those treated with animal-based fertilizers [136]. Given the higher cost of alfalfa meal, the authors concluded that while plant-based fertilizers might be ideal for improving soil and the quality of artichoke heads, animal-based fertilizers might be a more suitable choice for organic farmers when yield and cost are primary considerations. Another study conducted by Ogles et al. (2015) over two years evaluated the effectiveness of an organic fish fertilizer in a squash/collard rotation [137]. Although the yields did not significantly differ from those obtained using inorganic sources, economic analyses indicated that the premium prices and potential profits associated with organic products could make organic farming a financially viable option. Additionally, a study conducted between 1993 and 1995 in Taiwan and the Philippines explored the use of legume green manure (GM) as an alternative to mineral nitrogen fertilizer for tomatoes. The research revealed that GM, particularly soybean GM, significantly improved tomato yields in certain conditions, comparable to yields with traditional nitrogen fertilizers. However, the effectiveness of GM varied with the season and location, with better results in the wet season and on infertile soils. The study also highlighted that legume GM positively influenced the subsequent crop (maize) in the crop rotation, indicating a beneficial residual effect on soil fertility [138].

7. Perspective and Future

Organic farming, with its emphasis on sustainability and environmental stewardship, presents both opportunities and challenges in the context of a growing global population and high-demand crops like corn, soybean, and rice. A key feature of organic farming is the use of slow-release fertilizers, which, while beneficial for soil health and long-term sustainability, may pose limitations in meeting the immediate nutrient demands of these high-yield crops. This inherent nutrient limitation in organic systems raises concerns about their ability to match the expected growth rate necessary for feeding the increasing population. Though organic farming may not be providing the much-needed nutrients at a rate crop demands, the long-term application of organic fertilizer, especially manure, can improve the system resiliency to abiotic stresses like drought and can significantly improve the soil organic matter and health and sustain a more stable yield compared to inorganic fertilizers. However, it is important to note that organic farming encompasses more than just production methods; it adopts a holistic approach to building self-sustaining communities. Strategies like reducing food waste through composting and fostering networks of self-sufficient organic farmers play a vital role. These initiatives contribute to sustainable future by alleviating some pressure on production demands and creating localized food systems that rely less on large-scale agricultural practices, thereby mitigating the environmental impact. Farm-to-table practices further support these goals by reducing the carbon footprint associated with food transportation and promoting local production. In essence, while organic farming may face challenges in meeting the immediate production demands for certain crops, its broader approach to creating a more sustainable and self-reliant agricultural ecosystem offers a compelling path towards balancing production needs with environmental and social sustainability (Figure 2), which is a critical aspect in the creation of a sustainable agricultural system [139].

Figure 2. A multifaceted approach to sustainable agriculture, encompassing environmental, economic, and social dimensions. Illustrated is a vibrant community garden, a bustling marketplace, and an efficient composting area. The garden symbolizes environmental sustainability through organic farming and biodiversity conservation. The marketplace represents economic sustainability, showcasing the direct sale of locally grown produce, thereby supporting the local economy and reducing food miles. The composting area highlights waste reduction and nutrient recycling, which are essential for sustainable resource management. Additionally, this setup fosters social sustainability by enhancing community engagement, providing employment opportunities, and improving the overall quality of life for residents. (Note: the image was created with ChatGPT with a specific user-defined prompt to represent the author's perspective).

As scientific knowledge and technological advancement progress, organic farming presents numerous opportunities to meet consumer demands while addressing environmental stewardship. Key challenges that need addressing for the proper establishment of organic farming include understanding how organic fertilizers behave in the soil system, determining the timing of nutrient availability, and developing precise nutrient recommendation plans. Modern technologies, such as isotope tracing, can be used to understand the rate of mineralization and nutrient uptake. The effects of microbial activity on the mineralization dynamics of organic fertilizers can be evaluated using metagenomics and metabolomics studies [140]. Controlled environmental field studies are instrumental in understanding the impact of soil type, crop species, and climate on organic fertilizer dynamics. All this information can be utilized to develop simulation models to calculate the time required for plant-available nutrients from different organic fertilizers under varying temperatures, moisture, and soil conditions. Leveraging big data analytics and machine learning, agronomists can develop more accurate nutrient recommendation models [141]. These models can analyze historical data, current soil and crop conditions, and predictions about environmental changes to provide farmers with tailored advice on the optimal application of organic fertilizers. Research into combined organic–inorganic fertilizer formulations represents a significant advancement. These hybrid fertilizers aim to balance the immediate efficacy of inorganic nutrients with the long-term benefits of organic matter. By optimizing the ratio and composition of these fertilizers, farmers can reduce their dependency on purely organic or inorganic inputs, achieving a more sustainable and balanced nutrition plan for crops [142,143]. Utilizing technologies like remote sensing and AI-driven image analysis, farmers can more effectively monitor pest populations. This real-time monitoring allows for timely interventions, minimizing crop damage. Integrating these data with crop scheduling algorithms ensures that planting and harvesting are optimized based on pest life cycles, reducing infestations and improving yield [144]. Weed management remains a challenge, and the use of tillage is often questioned and criticized in organic farming due to reports of high soil erosion. Recent advances in weed management, including robotic weed control [145], electric weed elimination [146], and laser-based techniques [147], can be revolutionary for organic farming. These methods offer precise and eco-friendly alternatives to manual weeding, mechanical weeding, or chemical herbicides. Precision agriculture technologies enable variable rate fertilization, tailoring nutrient application to the specific needs of different crop areas. Informed by soil testing, remote sensing, and crop modeling, this approach ensures that each part of the field receives the right amount of nutrients at the right time, enhancing efficiency and reducing waste.

Implementing these innovations require addressing challenges like cost, accessibility, and farmer training. While technology offers new opportunities for understanding and optimizing nutrient dynamics, integrating these tools with traditional organic farming knowledge is essential. This integration ensures that technological advancements are applied in a way that respects and enhances the natural processes central to organic farming. Addressing challenges, like ensuring small-scale farmer's access and maintaining data privacy, is crucial. Developing best practices and guidelines ensures effective and sustainable technology use in organic farming.

Author Contributions: Conceptualization, D.P., S.D. and A.G.; Investigation, D.P. and S.D.; Writing—original draft preparation, D.P., N.B. and S.D.; Writing—review and editing, D.P., N.B., S.D. and A.G.; Funding acquisition, S.D. All authors have read and agreed to the published version of the manuscript.

Funding: This work was made possible by funding from the Pennsylvania Department of Agriculture's Commonwealth Specialty Crop Block Grant Program through grant number C940000924. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the PDA. This work was also funded by a private donation from Pocono Organics.

Acknowledgments: The authors express their gratitude to Chris Belluzzi, Sage Dennis, and Sam Malriat for their invaluable support during the preparation of the manuscript.

Conflicts of Interest: The authors declare that there are no conflicts of interest.

References

1. OTA. Organic Food Sales Break through $60 Billion in 2022 | OTA. Available online: https://ota.com/news/press-releases/22820 (accessed on 29 September 2023).
2. Kennedy, C.M.; Lonsdorf, E.; Neel, M.C.; Williams, N.M.; Ricketts, T.H.; Winfree, R.; Bommarco, R.; Brittain, C.; Burley, A.L.; Cariveau, D.; et al. A Global Quantitative Synthesis of Local and Landscape Effects on Wild Bee Pollinators in Agroecosystems. *Ecol. Lett.* **2013**, *16*, 584–599. [CrossRef]
3. Seufert, V.; Ramankutty, N. Many Shades of Gray—The Context-Dependent Performance of Organic Agriculture. *Sci. Adv.* **2017**, *3*, e1602638. [CrossRef] [PubMed]
4. Crowder, D.W.; Reganold, J.P. Financial Competitiveness of Organic Agriculture on a Global Scale. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 7611–7616. [CrossRef] [PubMed]
5. Reganold, J.P.; Wachter, J.M. Organic Agriculture in the Twenty-First Century. *Nat. Plants* **2016**, *2*, 15221. [CrossRef] [PubMed]
6. Larkin, R.P. Effects of Selected Soil Amendments and Mulch Type on Soil Properties and Productivity in Organic Vegetable Production. *Agronomy* **2020**, *10*, 795. [CrossRef]
7. Huntley, E.E.; Baker, A.V.; Stratton, M.L. Composition and Uses of Organic Fertilizers. In *Agricultural Uses of By-Products and Wastes*; American Chemical Society: Washington, DC, USA, 1997; pp. 120–139.
8. Claassen, V.P.; Carey, J.L. Comparison of Slow-Release Nitrogen Yield from Organic Soil Amendments and Chemical Fertilizers and Implications for Regeneration of Disturbed Sites. *Land Degrad. Dev.* **2007**, *18*, 119–132. [CrossRef]
9. Lim, S.L.; Wu, T.Y.; Lim, P.N.; Shak, K.P.Y. The Use of Vermicompost in Organic Farming: Overview, Effects on Soil and Economics. *J. Sci. Food Agric.* **2015**, *95*, 1143–1156. [CrossRef] [PubMed]

10. Gaskell, M.; Smith, R. Nitrogen Sources for Organic Vegetable Crops. *HortTechnology* **2007**, *17*, 431–441. [CrossRef]
11. Möller, K. Soil Fertility Status and Nutrient Input–Output Flows of Specialised Organic Cropping Systems: A Review. *Nutr. Cycl. Agroecosyst.* **2018**, *112*, 147–164. [CrossRef]
12. Twarog, S. Organic Agriculture: A Trade and Sustainable Development Opportunity for Developing Countries. Available online: https://www.un-ilibrary.org/content/books/9789211556469c007 (accessed on 29 September 2023).
13. Harwood, R.R. A History of Sustainable Agriculture. In *Sustainable Agricultural Systems*; CRC Press: Boca Raton, FL, USA, 1990; ISBN 978-1-00-307047-4.
14. Howard, A. *The Soil and Health: A Study of Organic Agriculture*; University Press of Kentucky: Lexington, KY, USA, 1947; ISBN 978-0-8131-9171-3.
15. Balfour, E.B. *The Living Soil: Evidence of the Importance to Human Health of Soil Vitality, with Special Reference to Post-War Planning*; Faber and Faber: London, UK, 1943.
16. Rodale, J.I. *The Organic Front*, 1st ed.; Rodale Press: New York, NY, USA, 1948.
17. Carson, R. *Silent Spring*; Hoghton Mifflin: Boston, MA, USA, 1962.
18. Lockeretz, W. *Organic Farming: An International History*; CABI: Wallingford, UK, 2007.
19. Dimitri, C.; Greene, C.R. Recent Growth Patterns In The U.S. Organic Foods Market. In *Agricultural Information Bulletins*; US Department of Agriculture, Economic Research Service: Washington, DC, USA, 2002.
20. Willer, H.; Kilcher, L. *The World of Organic Agriculture—Statistics and Emerging Trends 2011*; Willer, H., Kilcher, L., Eds.; IFOAM, Bonn and FiBL, Frick: New York, NY, USA, 2011.
21. Paull, J. From France to the World: The International Federation of Organic Agriculture Movements (IFOAM). Available online: https://orgprints.org/id/eprint/18808/ (accessed on 29 September 2023).
22. Yussefi, M.; Willer, H. *The World of Organic Agriculture 2003—Statistics and Future Prospects*; International Federation of Organic Agriculture Movements: Bonn, Germany, 2003.
23. Guthman, J. *Agrarian Dreams: The Paradox of Organic Farming in California*, 2nd ed.; University California Press: Oakland, CA, USA, 2014; ISBN 978-0-520-27746-5.
24. Rhodes, C.J. Feeding and Healing the World: Through Regenerative Agriculture and Permaculture. *Sci. Prog.* **2012**, *95*, 345–446. [CrossRef]
25. Godfray, H.C.J.; Beddington, J.R.; Crute, I.R.; Haddad, L.; Lawrence, D.; Muir, J.F.; Pretty, J.; Robinson, S.; Thomas, S.M.; Toulmin, C. Food Security: The Challenge of Feeding 9 Billion People. *Science* **2010**, *327*, 812–818. [CrossRef]
26. Rodale Institute. *Farming Systems Trial: 40-Year Report*; Rodale Institute: Kutztown, PA, USA, 2022.
27. Horlings, L.G.; Marsden, T.K. Towards the Real Green Revolution? Exploring the Conceptual Dimensions of a New Ecological Modernisation of Agriculture That Could 'Feed the World'. *Glob. Environ. Chang.* **2011**, *21*, 441–452. [CrossRef]
28. Sahota, A. Overview of the Global Market for Organic Food and Drink. In *The World of Organic Agricuture: Statistics & Emerging Trends*; IFOAM: Bonn, Germany, 2004.
29. Willer, H.; Lernoud, J. *The World of Organic Agriculture Statistics and Emerging Trends 2019*; IFOAM: Bonn, Germany, 2019.
30. Global Agriculture over 76.4 Million Hectares Were Farmed Organically Worldwide in 2021. Available online: https://www.globalagriculture.org/whats-new/news/en/34731.html (accessed on 29 September 2023).
31. Statista. *Worldwide Sales of Organic Food from 1999 to 2021*; Statista: Hamburg, Germany, 2023.
32. Stolze, M.; Piorr, A.; Häring, A.M.; Dabbert, S. *Environmental Impacts of Organic Farming in Europe*; Universität Hohenheim: Stuttgart, Germany, 2000.
33. Lotter, D.W.; Seidel, R.; Liebhardt, W. The Performance of Organic and Conventional Cropping Systems in an Extreme Climate Year. *Am. J. Altern. Agric.* **2003**, *18*, 146–154. [CrossRef]
34. Colla, G.; Mitchell, J.P.; Joyce, B.A.; Huyck, L.M.; Wallender, W.W.; Temple, S.R.; Hsiao, T.C.; Poudel, D.D. Soil Physical Properties and Tomato Yield and Quality in Alternative Cropping Systems. *Agron. J.* **2000**, *92*, 924–932. [CrossRef]
35. Bengtsson, J.; Ahnström, J.; Weibull, A.-C. The Effects of Organic Agriculture on Biodiversity and Abundance: A Meta-Analysis. *J. Appl. Ecol.* **2005**, *42*, 261–269. [CrossRef]
36. Seitz, S.; Goebes, P.; Puerta, V.L.; Pereira, E.I.P.; Wittwer, R.; Six, J.; van der Heijden, M.G.A.; Scholten, T. Conservation Tillage and Organic Farming Reduce Soil Erosion. *Agron. Sustain. Dev.* **2018**, *39*, 4. [CrossRef]
37. Pimentel, D.; Hepperly, P.; Hanson, J.; Douds, D.; Seidel, R. Environmental, Energetic, and Economic Comparisons of Organic and Conventional Farming Systems. *BioScience* **2005**, *55*, 573–582. [CrossRef]
38. Das, S.; Liptzin, D.; Maharjan, B. Long-Term Manure Application Improves Soil Health and Stabilizes Carbon in Continuous Maize Production System. *Geoderma* **2023**, *430*, 116338. [CrossRef]
39. Grand View Research. Organic Food and Beverages Market Size Report, 2030. Available online: https://www.grandviewresearch.com/industry-analysis/organic-foods-beverages-market (accessed on 23 September 2023).
40. Barański, M.; Średnicka-Tober, D.; Volakakis, N.; Seal, C.; Sanderson, R.; Stewart, G.B.; Benbrook, C.; Biavati, B.; Markellou, E.; Giotis, C.; et al. Higher Antioxidant and Lower Cadmium Concentrations and Lower Incidence of Pesticide Residues in Organically Grown Crops: A Systematic Literature Review and Meta-Analyses. *Br. J. Nutr.* **2014**, *112*, 794–811. [CrossRef] [PubMed]

41. Mitchell, A.E.; Hong, Y.-J.; Koh, E.; Barrett, D.M.; Bryant, D.E.; Denison, R.F.; Kaffka, S. Ten-Year Comparison of the Influence of Organic and Conventional Crop Management Practices on the Content of Flavonoids in Tomatoes. *J. Agric. Food Chem.* **2007**, *55*, 6154–6159. [CrossRef]
42. Forman, J.; Silverstein, J.; Committee on Nutrition; Council on Environmental Health. American Academy of Pediatrics Organic Foods: Health and Environmental Advantages and Disadvantages. *Pediatrics* **2012**, *130*, e1406–e1415. [CrossRef]
43. Gosling, P.; Shepherd, M. Long-Term Changes in Soil Fertility in Organic Arable Farming Systems in England, with Particular Reference to Phosphorus and Potassium. *Agric. Ecosyst. Environ.* **2005**, *105*, 425–432. [CrossRef]
44. Muluneh, M.W.; Talema, G.A.; Abebe, K.B.; Dejen Tsegaw, B.; Kassaw, M.A.; Teka Mebrat, A. Determinants of Organic Fertilizers Utilization Among Smallholder Farmers in South Gondar Zone, Ethiopia. *Environ. Health Insights* **2022**, *16*, 11786302221075448. [CrossRef]
45. Altieri, M.A. The Ecological Role of Biodiversity in Agroecosystems. *Agric. Ecosyst. Environ.* **1999**, *74*, 19–31. [CrossRef]
46. Burnett, S.E.; Stack, L.B. Survey of the Research Needs of the Potential Organic Ornamental Bedding Plant Industry in Maine. *HortTechnology* **2009**, *19*, 743–747. [CrossRef]
47. Burnett, S.E.; Mattson, N.S.; Williams, K.A. Substrates and Fertilizers for Organic Container Production of Herbs, Vegetables, and Herbaceous Ornamental Plants Grown in Greenhouses in the United States. *Sci. Hortic.* **2016**, *208*, 111–119. [CrossRef]
48. Bergstrand, K.-J. Organic Fertilizers in Greenhouse Production Systems—A Review. *Sci. Hortic.* **2022**, *295*, 110855. [CrossRef]
49. Seufert, V.; Ramankutty, N.; Foley, J.A. Comparing the Yields of Organic and Conventional Agriculture. *Nature* **2012**, *485*, 229–232. [CrossRef] [PubMed]
50. de Ponti, T.; Rijk, B.; van Ittersum, M.K. The Crop Yield Gap between Organic and Conventional Agriculture. *Agric. Syst.* **2012**, *108*, 1–9. [CrossRef]
51. Melander, B.; Nørremark, M.; Kristensen, E.F. Combining Mechanical Rhizome Removal and Cover Crops for Elytrigia Repens Control in Organic Barley Systems. *Weed Res.* **2013**, *53*, 461–469. [CrossRef]
52. Lampkin, N.; Padel, S. *The Economics of Organic Farming: An International Perspective*; CAB International: Wallingford, UK, 1994; ISBN 978-0-85198-911-2.
53. Darnhofer, I.; Lindenthal, T.; Bartel-Kratochvil, R.; Zollitsch, W. Conventionalisation of Organic Farming Practices: From Structural Criteria towards an Assessment Based on Organic Principles. A Review. *Agron. Sustain. Dev.* **2010**, *30*, 67–81. [CrossRef]
54. Maharjan, B.; Das, S.; Nielsen, R.; Hergert, G.W. Maize Yields from Manure and Mineral Fertilizers in the 100-Year-Old Knorr–Holden Plot. *Agron. J.* **2021**, *113*, 5383–5397. [CrossRef]
55. Van Es, H.M.; Schindelbeck, R.R.; Jokela, W.E. Effect of Manure Application Timing, Crop, and Soil Type on Phosphorus Leaching. *J. Environ. Qual.* **2004**, *33*, 1070–1080. [CrossRef]
56. Van Es, H.M.; Sogbedji, J.M.; Schindelbeck, R.R. Effect of Manure Application Timing, Crop, and Soil Type on Nitrate Leaching. *J. Environ. Qual.* **2006**, *35*, 670–679. [CrossRef]
57. Erwiha, G.M.; Ham, J.; Sukor, A.; Wickham, A.; Davis, J.G. Organic Fertilizer Source and Application Method Impact Ammonia Volatilization. *Commun. Soil Sci. Plant Anal.* **2020**, *51*, 1469–1482. [CrossRef]
58. Chadwick, D.; Sommer, S.; Thorman, R.; Fangueiro, D.; Cardenas, L.; Amon, B.; Misselbrook, T. Manure Management: Implications for Greenhouse Gas Emissions. *Anim. Feed Sci. Technol.* **2011**, *166–167*, 514–531. [CrossRef]
59. Bicudo, J.R.; Goyal, S.M. Pathogens and Manure Management Systems: A Review. *Environ. Technol.* **2003**, *24*, 115–130. [CrossRef]
60. Ciavatta, C.; Govi, M.; Sitti, L.; Gessa, C. Influence of Blood Meal Organic Fertilizer on Soil Organic Matter: A Laboratory Study. *J. Plant Nutr.* **1997**, *20*, 1573–1591. [CrossRef]
61. Yunta, F.; Di Foggia, M.; Bellido-Díaz, V.; Morales-Calderón, M.; Tessarin, P.; López-Rayo, S.; Tinti, A.; Kovács, K.; Klencsár, Z.; Fodor, F. Blood Meal-Based Compound. Good Choice as Iron Fertilizer for Organic Farming. *J. Agric. Food Chem.* **2013**, *61*, 3995–4003. [CrossRef]
62. Maltais-Landry, G.; Buchanan, C.; Longanecker, J. Using Processed Fertilizers or Composted Poultry Manure Results in Similar Yields but Contrasting Nutrient Budgets in Organic Cabbage Production. *J. Plant Nutr.* **2023**, *46*, 2462–2472. [CrossRef]
63. Cherr, C.M.; Scholberg, J.M.S.; McSorley, R. Green Manure Approaches to Crop Production: A Synthesis. *Agron. J.* **2006**, *98*, 302–319. [CrossRef]
64. Raghunandan, B.L.; Vyas, R.V.; Patel, H.K.; Jhala, Y.K. Perspectives of Seaweed as Organic Fertilizer in Agriculture. In *Soil Fertility Management for Sustainable Development*; Panpatte, D.G., Jhala, Y.K., Eds.; Springer: Singapore, 2019; pp. 267–289, ISBN 9789811359040.
65. Ho, T.T.K.; Tra, V.T.; Le, T.H.; Nguyen, N.-K.-Q.; Tran, C.-S.; Nguyen, P.-T.; Vo, T.-D.-H.; Thai, V.-N.; Bui, X.-T. Compost to Improve Sustainable Soil Cultivation and Crop Productivity. *Case Stud. Chem. Environ. Eng.* **2022**, *6*, 100211. [CrossRef]
66. Skeen, J.R. Greensand as a Source of Potassium for Green Plants. *Am. J. Bot.* **1925**, *12*, 607–616. [CrossRef]
67. Kamprath, E.J.; Foy, C.D. Lime-Fertilizer-Plant Interactions in Acid Soils. In *Fertilizer Technology and Use*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 1985; pp. 91–151. ISBN 978-0-89118-871-1.
68. Dimande, P.; Arrobas, M.; Rodrigues, M.Â. Effect of Bat Guano and Biochar on Okra Yield and Some Soil Properties. *Horticulturae* **2023**, *9*, 728. [CrossRef]
69. Lehmann, J.; Cowie, A.; Masiello, C.A.; Kammann, C.; Woolf, D.; Amonette, J.E.; Cayuela, M.L.; Camps-Arbestain, M.; Whitman, T. Biochar in Climate Change Mitigation. *Nat. Geosci.* **2021**, *14*, 883–892. [CrossRef]

70. Mitter, E.K.; Tosi, M.; Obregón, D.; Dunfield, K.E.; Germida, J.J. Rethinking Crop Nutrition in Times of Modern Microbiology: Innovative Biofertilizer Technologies. *Front. Sustain. Food Syst.* **2021**, *5*, 606815. [CrossRef]
71. Wen, A.; Havens, K.L.; Bloch, S.E.; Shah, N.; Higgins, D.A.; Davis-Richardson, A.G.; Sharon, J.; Rezaei, F.; Mohiti-Asli, M.; Johnson, A.; et al. Enabling Biological Nitrogen Fixation for Cereal Crops in Fertilized Fields. *ACS Synth. Biol.* **2021**, *10*, 3264–3277. [CrossRef]
72. Marchuk, S.; Tait, S.; Sinha, P.; Harris, P.; Antille, D.L.; McCabe, B.K. Biosolids-Derived Fertilisers: A Review of Challenges and Opportunities. *Sci. Total Environ.* **2023**, *875*, 162555. [CrossRef] [PubMed]
73. Emmanouil, C.; Bekyrou, M.; Psomopoulos, C.; Kungolos, A. An Insight into Ingredients of Toxicological Interest in Personal Care Products and A Small–Scale Sampling Survey of the Greek Market: Delineating a Potential Contamination Source for Water Resources. *Water* **2019**, *11*, 2501. [CrossRef]
74. Tran, N.H.; Reinhard, M.; Gin, K.Y.-H. Occurrence and Fate of Emerging Contaminants in Municipal Wastewater Treatment Plants from Different Geographical Regions-a Review. *Water Res.* **2018**, *133*, 182–207. [CrossRef] [PubMed]
75. Koenig, R.; Johnson, M. *Selecting and Using Organic Fertilizers*; Utah State University: Logan, UT, USA, 2011.
76. Gross, A.; Glaser, B. Meta-Analysis on How Manure Application Changes Soil Organic Carbon Storage. *Sci. Rep.* **2021**, *11*, 5516. [CrossRef]
77. Brock, E.H.; Ketterings, Q.M.; Kleinman, P.J.A. Phosphorus Leaching through Intact Soil Cores as Influenced by Type and Duration of Manure Application. *Nutr. Cycl. Agroecosyst.* **2007**, *77*, 269–281. [CrossRef]
78. Hao, X.; Chang, C. Does Long-Term Heavy Cattle Manure Application Increase Salinity of a Clay Loam Soil in Semi-Arid Southern Alberta? *Agric. Ecosyst. Environ.* **2003**, *94*, 89–103. [CrossRef]
79. Kalbasi, M.; Shariatmadari, H. Blood Powder, a Source of Iron for Plants. *J. Plant Nutr.* **1993**, *16*, 2213–2223. [CrossRef]
80. Załuszniewska, A.; Nogalska, A. The Effect of Meat and Bone Meal (MBM) on Phosphorus (P) Content and Uptake by Crops, and Soil Available P Balance in a Six-Year Field Experiment. *Sustainability* **2022**, *14*, 2855. [CrossRef]
81. Hartz, T.K.; Johnstone, P.R. Nitrogen Availability from High-Nitrogen-Containing Organic Fertilizers. *HortTechnology* **2006**, *16*, 39–42. [CrossRef]
82. Lazzari, R.; Baldisserotto, B. Excreção de nitrogênio e fósforo em pisciculturas. *Bol. Inst. Pesca* **2008**, *34*, 591–600.
83. Hadas, A.; Kautsky, L. Feather Meal, a Semi-Slow-Release Nitrogen Fertilizer for Organic Farming. *Fertil. Res.* **1994**, *38*, 165–170. [CrossRef]
84. Kranz, C.N.; McLaughlin, R.A.; Johnson, A.; Miller, G.; Heitman, J.L. The Effects of Compost Incorporation on Soil Physical Properties in Urban Soils—A Concise Review. *J. Environ. Manag.* **2020**, *261*, 110209. [CrossRef]
85. Ahmad, S.; Khalid, R.; Abbas, S.; Hayat, R.; Ahmed, I. Chapter 6—Potential of Compost for Sustainable Crop Production and Soil Health. In *Recent Advancement in Microbial Biotechnology*; De Mandal, S., Passari, A.K., Eds.; Academic Press: Cambridge, MA, USA, 2021; pp. 123–170. ISBN 978-0-12-822098-6.
86. Wright, J.; Kenner, S.; Lingwall, B. Utilization of Compost as a Soil Amendment to Increase Soil Health and to Improve Crop Yields. *Open J. Soil Sci.* **2022**, *12*, 216–224. [CrossRef]
87. Blouin, M.; Barrere, J.; Meyer, N.; Lartigue, S.; Barot, S.; Mathieu, J. Vermicompost Significantly Affects Plant Growth. A Meta-Analysis. *Agron. Sustain. Dev.* **2019**, *39*, 34. [CrossRef]
88. Olle, M. Review: Bokashi Technology as a Promising Technology for Crop Production in Europe. *J. Hortic. Sci. Biotechnol.* **2021**, *96*, 145–152. [CrossRef]
89. Footer, A. *Bokashi Composting: Scraps to Soil in Weeks*; New Society Publishers: Gabriola Island, BC, Canada, 2013; ISBN 978-0-86571-752-7.
90. Fageria, N.K. Green Manuring in Crop Production. *J. Plant Nutr.* **2007**, *30*, 691–719. [CrossRef]
91. Kumar, S.; Samiksha; Sukul, P. Green Manuring and Its Role in Soil Health Managemen. In *Soil Health*; Giri, B., Varma, A., Eds.; Soil Biology; Springer International Publishing: Cham, Switzerland, 2020; pp. 219–241. ISBN 978-3-030-44364-1.
92. Meena, B.L.; Fagodiya, R.K.; Prajapat, K.; Dotaniya, M.L.; Kaledhonkar, M.J.; Sharma, P.C.; Meena, R.S.; Mitran, T.; Kumar, S. Legume Green Manuring: An Option for Soil Sustainability. In *Legumes for Soil Health and Sustainable Management*; Meena, R.S., Das, A., Yadav, G.S., Lal, R., Eds.; Springer: Singapore, 2018; pp. 387–408. ISBN 9789811302534.
93. Atkins, F.M.; Wilson, M.; Bock, S.A. Cottonseed Hypersensitivity: New Concerns over an Old Problem. *J. Allergy Clin. Immunol.* **1988**, *82*, 242–250. [CrossRef] [PubMed]
94. Spiers, J.M. Effect of Fertilization Rates and Sources on Rabbiteye Blueberry. *J. Am. Soc. Hortic. Sci.* **1987**, *112*, 600–603. [CrossRef]
95. Chalker-Scott, L. *The Efficacy and Environmental Consequences of Kelp-Based Garden Products*; Washington State University: Pullman, WA, USA, 2019.
96. Singh, S.; Singh, J.; Vig, A.P. Earthworm as Ecological Engineers to Change the Physico-Chemical Properties of Soil: Soil vs. Vermicast. *Ecol. Eng.* **2016**, *90*, 1–5. [CrossRef]
97. Novak, J.; Sigua, G.; Watts, D.; Cantrell, K.; Shumaker, P.; Szogi, A.; Johnson, M.G.; Spokas, K. Biochars Impact on Water Infiltration and Water Quality through a Compacted Subsoil Layer. *Chemosphere* **2016**, *142*, 160–167. [CrossRef] [PubMed]
98. Sohi, S.P.; Krull, E.; Lopez-Capel, E.; Bol, R. Chapter 2—A Review of Biochar and Its Use and Function in Soil. In *Advances in Agronomy*; Academic Press: Cambridge, MA, USA, 2010; Volume 105, pp. 47–82.
99. Espoma Espoma Organic Greensand | Espoma. Available online: https://www.espoma.com/product/greensand/ (accessed on 26 December 2023).

100. Suciu, N.A.; De Vivo, R.; Rizzati, N.; Capri, E. Cd Content in Phosphate Fertilizer: Which Potential Risk for the Environment and Human Health? *Curr. Opin. Environ. Sci. Health* **2022**, *30*, 100392. [CrossRef]
101. Hu, H.-Q.; Li, X.-Y.; Liu, J.-F.; Xu, F.-L.; Liu, J.; Liu, F. The Effect of Direct Application of Phosphate Rock on Increasing Crop Yield and Improving Properties of Red Soil. *Nutr. Cycl. Agroecosyst.* **1996**, *46*, 235–239. [CrossRef]
102. Marschner, B.; Waldemar Wilczynski, A. The Effect of Liming on Quantity and Chemical Composition of Soil Organic Matter in a Pine Forest in Berlin, Germany. *Plant Soil* **1991**, *137*, 229–236. [CrossRef]
103. Brown, T.T.; Koenig, R.T.; Huggins, D.R.; Harsh, J.B.; Rossi, R.E. Lime Effects on Soil Acidity, Crop Yield, and Aluminum Chemistry in Direct-Seeded Cropping Systems. *Soil Sci. Soc. Amer. J.* **2008**, *72*, 634–640. [CrossRef]
104. Wang, X.; Tang, C.; Baldock, J.A.; Butterly, C.R.; Gazey, C. Long-Term Effect of Lime Application on the Chemical Composition of Soil Organic Carbon in Acid Soils Varying in Texture and Liming History. *Biol. Fertil. Soils* **2016**, *52*, 295–306. [CrossRef]
105. Enesi, R.O.; Dyck, M.; Chang, S.; Thilakarathna, M.S.; Fan, X.; Strelkov, S.; Gorim, L.Y. Liming Remediates Soil Acidity and Improves Crop Yield and Profitability—A Meta-Analysis. *Front. Agron.* **2023**, *5*, 1194896. [CrossRef]
106. MSU. Facts about Soil Acidity and Lime (E1566). Available online: https://www.canr.msu.edu/resources/facts_about_soil_acidity_and_lime_e1566 (accessed on 26 December 2023).
107. Nogalska, A.; Załuszniewska, A. The Effect of Meat and Bone Meal (MBM) on Crop Yields, Nitrogen Content and Uptake, and Soil Mineral Nitrogen Balance. *Agronomy* **2021**, *11*, 2307. [CrossRef]
108. Stępień, A.; Wojtkowiak, K. Effect of Meat and Bone Meal and Effective Microorganisms on Content and Composition of Protein in Crops Part I. Spring Wheat. *Acta Sci. Pol. Agric.* **2011**, *10*, 143–152.
109. Silvasy, T.; Ahmad, A.A.; Wang, K.-H.; Radovich, T.J.K. Rate and Timing of Meat and Bone Meal Applications Influence Growth, Yield, and Soil Water Nitrate Concentrations in Sweet Corn Production. *Agronomy* **2021**, *11*, 1945. [CrossRef]
110. Nogalska, A. Changes in the Soil Nitrogen Content Caused by Direct and Residual Effect of Meat and Bone Meal. *J. Elem.* **2014**, *18*, 659–671. [CrossRef]
111. Azeem, M.; Ali, A.; Arockiam Jeyasundar, P.G.S.; Li, Y.; Abdelrahman, H.; Latif, A.; Li, R.; Basta, N.; Li, G.; Shaheen, S.M.; et al. Bone-Derived Biochar Improved Soil Quality and Reduced Cd and Zn Phytoavailability in a Multi-Metal Contaminated Mining Soil. *Environ. Pollut.* **2021**, *277*, 116800. [CrossRef]
112. Abbasi, P.A.; Conn, K.L.; Lazarovits, G. Suppression of *Rhizoctonia* and *Pythium* Damping-off of Radish and Cucumber Seedlings by Addition of Fish Emulsion to Peat Mix or Soil. *Can. J. Plant Pathol.* **2004**, *26*, 177–187. [CrossRef]
113. Abbasi, P.A.; Conn, K.L.; Lazarovits, G. Effect of Fish Emulsion Used as a Preplanting Soil Amendment on Verticillium Wilt, Scab, and Tuber Yield of Potato. *Can. J. Plant Pathol.* **2006**, *28*, 509–518. [CrossRef]
114. Castro, R.S.; Borges Azevedo, C.M.S.; Bezerra-Neto, F. Increasing Cherry Tomato Yield Using Fish Effluent as Irrigation Water in Northeast Brazil. *Sci. Hortic.* **2006**, *110*, 44–50. [CrossRef]
115. Tsuruta, T.; Yamaguchi, M.; Abe, S.; Iguchi, K. Effect of Fish in Rice-Fish Culture on the Rice Yield. *Fish. Sci.* **2011**, *77*, 95–106. [CrossRef]
116. Hussain, H.I.; Kasinadhuni, N.; Arioli, T. The Effect of Seaweed Extract on Tomato Plant Growth, Productivity and Soil. *J. Appl. Phycol.* **2021**, *33*, 1305–1314. [CrossRef]
117. Margal, P.B.; Thakare, R.S.; Kamble, B.M.; Patil, V.S.; Patil, K.B.; Titirmare, N.S. Effect of Seaweed Extracts on Crop Growth and Soil: A Review. *JEAI* **2023**, *45*, 9–19. [CrossRef]
118. Nanda, S.; Kumar, G.; Hussain, S. Utilization of Seaweed-Based Biostimulants in Improving Plant and Soil Health: Current Updates and Future Prospective. *Int. J. Environ. Sci. Technol.* **2022**, *19*, 12839–12852. [CrossRef]
119. Filippini, M.; Baldisserotto, A.; Menotta, S.; Fedrizzi, G.; Rubini, S.; Gigliotti, D.; Valpiani, G.; Buzzi, R.; Manfredini, S.; Vertuani, S. Heavy Metals and Potential Risks in Edible Seaweed on the Market in Italy. *Chemosphere* **2021**, *263*, 127983. [CrossRef] [PubMed]
120. Peng, Z.; Guo, Z.; Wang, Z.; Zhang, R.; Wu, Q.; Gao, H.; Wang, Y.; Shen, Z.; Lek, S.; Xiao, J. Species-Specific Bioaccumulation and Health Risk Assessment of Heavy Metal in Seaweeds in Tropic Coasts of South China Sea. *Sci. Total Environ.* **2022**, *832*, 155031. [CrossRef] [PubMed]
121. Naeem, M.; Khan, M.M.A. Moinuddin Triacontanol: A Potent Plant Growth Regulator in Agriculture. *J. Plant Interact.* **2012**, *7*, 129–142. [CrossRef]
122. Bhandari, S.; Bhandari, A.; Shrestha, J. Effect of Different Doses of Triacontanol on Growth and Yield of Kohlrabi (*Brassica olerацea* L. Var. *Gongylodes*). *Heliyon* **2021**, *7*, e08242. [CrossRef] [PubMed]
123. Wijesekara, H.; Bolan, N.S.; Thangavel, R.; Seshadri, B.; Surapaneni, A.; Saint, C.; Hetherington, C.; Matthews, P.; Vithanage, M. The Impact of Biosolids Application on Organic Carbon and Carbon Dioxide Fluxes in Soil. *Chemosphere* **2017**, *189*, 565–573. [CrossRef]
124. Ippolito, J.A.; Ducey, T.F.; Diaz, K.; Barbarick, K.A. Long-Term Biosolids Land Application Influences Soil Health. *Sci. Total Environ.* **2021**, *791*, 148344. [CrossRef]
125. Nicholson, F.; Bhogal, A.; Taylor, M.; McGrath, S.; Withers, P. Long-Term Effects of Biosolids on Soil Quality and Fertility. *Soil Sci.* **2018**, *183*, 89. [CrossRef]
126. Bamber, K.W.; Evanylo, G.K.; Thomason, W.E. Importance of Soil Properties on Recommended Biosolids Management for Winter Wheat. *Soil Sci. Soc. Am. J.* **2016**, *80*, 919–929. [CrossRef]
127. Zhang, X.; Ervin, E.H.; Evanylo, G.K.; Li, J.; Harich, K. Corn and Soybean Hormone and Antioxidant Metabolism Responses to Biosolids under Two Cropping Systems. *Crop Sci.* **2013**, *53*, 2079–2089. [CrossRef]

128. Badzmierowski, M.; Evanylo, D.G. *Biosolids Use for Row Crops, Forage, and Hay Lands*; Virgnia Tech: Blacksburg, VA, USA, 2023.
129. OMRI. About OMRI Listed Products. Available online: https://www.omri.org/about-omri-listed-products (accessed on 29 September 2023).
130. Olle, M.; Williams, I.H. Organic Farming of Vegetables. In *Sustainable Agriculture Reviews: Volume 11*; Lichtfouse, E., Ed.; Sustainable Agriculture Reviews; Springer: Dordrecht, The Netherlands, 2012; pp. 63–76. ISBN 978-94-007-5449-2.
131. Adekiya, A.O. Green Manures and Poultry Feather Effects on Soil Characteristics, Growth, Yield, and Mineral Contents of Tomato. *Sci. Hortic.* **2019**, *257*, 108721. [CrossRef]
132. Gao, F.; Li, H.; Mu, X.; Gao, H.; Zhang, Y.; Li, R.; Cao, K.; Ye, L. Effects of Organic Fertilizer Application on Tomato Yield and Quality: A Meta-Analysis. *Appl. Sci.* **2023**, *13*, 2184. [CrossRef]
133. Thomas, C.L.; Acquah, G.E.; Whitmore, A.P.; McGrath, S.P.; Haefele, S.M. The Effect of Different Organic Fertilizers on Yield and Soil and Crop Nutrient Concentrations. *Agronomy* **2019**, *9*, 776. [CrossRef]
134. Huang, L.; Cheng, S.; Liu, H.; Zhao, Z.; Wei, S.; Sun, S. Effects of Nitrogen Reduction Combined with Organic Fertilizer on Growth and Nitrogen Fate in Banana at Seedling Stage. *Environ. Res.* **2022**, *214*, 113826. [CrossRef] [PubMed]
135. El-Tarabily, K.A.; Nassar, A.H.; Hardy, G.E.S.J.; Sivasithamparam, K. Fish Emulsion as a Food Base for Rhizobacteria Promoting Growth of Radish (*Raphanus sativus* L. Var. *Sativus*) in a Sandy Soil. *Plant Soil* **2003**, *252*, 397–411. [CrossRef]
136. Othman, Y.A.; Leskovar, D. Organic Soil Amendments Influence Soil Health, Yield, and Phytochemicals of Globe Artichoke Heads. *Biol. Agric. Hortic.* **2018**, *34*, 258–267. [CrossRef]
137. Ogles, C.Z.; Kemble, J.M.; Wright, A.N.; Guertal, E.A. Evaluation of an Organic Nitrogen Source in a Yellow Squash–Collard Rotation. *HortScience* **2015**, *50*, 51–58. [CrossRef]
138. Thönnissen, C.; Midmore, D.J.; Ladha, J.K.; Holmer, R.J.; Schmidhalter, U. Tomato Crop Response to Short-Duration Legume Green Manures in Tropical Vegetable Systems. *Agron. J.* **2000**, *92*, 245–253. [CrossRef]
139. Das, S.; Ray, M.K.; Panday, D.; Mishra, P.K. Role of Biotechnology in Creating Sustainable Agriculture. *PLOS Sustain. Transform.* **2023**, *2*, e0000069. [CrossRef]
140. Liao, X.; Zhao, J.; Yi, Q.; Li, J.; Li, Z.; Wu, S.; Zhang, W.; Wang, K. Metagenomic Insights into the Effects of Organic and Inorganic Agricultural Managements on Soil Phosphorus Cycling. *Agric. Ecosyst. Environ.* **2023**, *343*, 108281. [CrossRef]
141. Timsina, J.; Dutta, S.; Devkota, K.P.; Chakraborty, S.; Neupane, R.K.; Bishta, S.; Amgain, L.P.; Singh, V.K.; Islam, S.; Majumdar, K. Improved Nutrient Management in Cereals Using Nutrient Expert and Machine Learning Tools: Productivity, Profitability and Nutrient Use Efficiency. *Agric. Syst.* **2021**, *192*, 103181. [CrossRef]
142. Robe, T.B. Review on: The Effect of Mixing Organic and Inorganic Fertilizer on Productivity and Soil Fertility. *Open Access Libr. J.* **2018**, *5*, 85548. [CrossRef]
143. Moe, K.; Mg, K.W.; Win, K.K.; Yamakawa, T. Combined Effect of Organic Manures and Inorganic Fertilizers on the Growth and Yield of Hybrid Rice (Palethwe-1). *Am. J. Plant Sci.* **2017**, *8*, 1022–1042. [CrossRef]
144. Dong, Y.; Xu, F.; Liu, L.; Du, X.; Ren, B.; Guo, A.; Geng, Y.; Ruan, C.; Ye, H.; Huang, W.; et al. Automatic System for Crop Pest and Disease Dynamic Monitoring and Early Forecasting. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2020**, *13*, 4410–4418. [CrossRef]
145. Slaughter, D.C.; Giles, D.K.; Downey, D. Autonomous Robotic Weed Control Systems: A Review. *Comput. Electron. Agric.* **2008**, *61*, 63–78. [CrossRef]
146. Sahin, H.; Yalınkılıc, M. Using Electric Current as a Weed Control Method. *Eur. J. Eng. Technol. Res.* **2017**, *2*, 59–64. [CrossRef]
147. Mathiassen, S.K.; Bak, T.; Christensen, S.; Kudsk, P. The Effect of Laser Treatment as a Weed Control Method. *Biosyst. Eng.* **2006**, *95*, 497–505. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.