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# Crop Nutrition and Soil Fertility Management in Organic Potato Production Systems

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**Abstract:** Organic farming is a comprehensive production management system that fosters and improves the health of agroecosystems, encompassing biodiversity, biological cycles, and soil biological activity. The potato (*Solanum tuberosum* L.) is a crucial crop in organic farming systems, standing out as one of the most highly demanded organic products on the market. Among all crops, with potatoes, there is a very large yield gap between organic and conventional systems, attributable mainly to its intensive nutrient demands. The present review, considering the most relevant scientific literature worldwide, discusses the contemporary state of knowledge on crop nutrition and soil fertility management in organic potato crop production, analyzing the effects of animal manures, green manures, organic amendments, and biostimulants on organic potato tuber yield and quality. Overall, the main findings show a particular combination is needed to effectively maintain good soil fertility, satisfy the nutritional needs of the crop, and overcome the difference in potato yield between organic and conventional farming methods while meeting consumer demand. This combination entails using an animal manure or leguminous green manure with an organic soil amendment, and even better with a biofertilizer, such as a mycorrhizae-fungus-based one. It also emerged that more targeted studies are needed to select appropriate cultivars for organic potato farming systems to optimize this environmentally friendly production method.

**Keywords:** potato; organic; crop nutrition; soil fertility; yield; quality

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**Citation:** Ierna, A.; Distefano, M. Crop Nutrition and Soil Fertility Management in Organic Potato Production Systems. *Horticulturae* **2024**, *10*, 886. https://doi.org/10.3390/horticulturae10080886

Academic Editors: Francesco Montemurro, Simona Fabroni and Luana Bontempo

Received: 25 July 2024
Revised: 11 August 2024
Accepted: 17 August 2024
Published: 21 August 2024

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## 1. Introduction

Interest in organic agriculture is growing worldwide, mainly supported by a strong consumer interest. This can be measured by the value of retail sales of organic products, which grew to an impressive 44.2 billion euros in the European Union (EU) [1]. The market trend is still growing and increasing faster than the organic farmland area. In 2020, in most of the EU-member states the organic farmland area increased; the biggest shares of the organic farmland area in the total utilized area are in Austria (26.5%), Estonia (22.4%), Sweden (20.4%) and Italy (16%) [1]. The potato (*Solanum tuberosum* L.), globally ranked as the fourth most significant food crop, with an annual production of approximately 400 million tons [2], is a crucial crop in organic farming systems, standing out as one of the most highly demanded organic products on the market [3]. Organic potato in EU-28 is cultivated in an area of 31,771 ha (average 2017–2019) [4], of which approximately half are in five countries, namely Germany (9345 ha), France (3370 ha), the Netherlands (1685 ha), United Kingdom (1234 ha), and Belgium (845 ha). Previous research comparing potato yields in conventional and organic production systems has often found significantly lower yields in organic systems [5]. Comparing various European countries across 21 aspects, it was found that organic potato yields accounted for only 70% of those from conventional crops [6]. When considering potatoes as a vegetable, the yield gap was almost 30%, as noted by Ponisio et al. [7]. Results of field experiment trials in potatoes for a long-term period demonstrated that the yield gap between conventional and organic farming systems was due to both less efficient crop protection and fertilization in organic systems [8–10]. It

was determined that 48% of the gap in organic potato yields can be attributed to reduced fertilization, and 25% to diseases, primarily late blight caused by *Phytophthora infestans* and the Colorado potato beetle (*Leptinotarsa decemlineata*) [11]. Moreover, the yield gap between organic and conventional fertilization regimes appears to be attributable mainly to the lower and less predictable nitrogen supply in organically fertilized crops [12].

A potato crop has high nutritional needs; indeed, to produce 1 ton of tubers requires approximately 4–5 kg of nitrogen, 0.7–0.8 kg of phosphorus, 5–6 kg of potassium, and significant quantities of microelements [13]. Furthermore, potato crops are characterized by a relatively low ability to uptake available soil mineral nitrogen [14]. Therefore, to better align N requirements with supply, it is common practice in conventional agriculture to split the application of N fertilizers [15,16]. Given this premise, it is understandable that organic potato fertilization is a real challenge. The efficacy of organic fertilization in organic systems depends on various factors, including the type of fertilizer used (quantity, timing), soil conditions, and weather patterns during the plant's growth stages. Unfavorable combinations of soil and climatic conditions can hinder the decomposition of applied fertilizers and the uptake of nutrients, leading to stress and developmental disorders in potato plants. As is known, potato tuber quality is influenced by climate, environment, genetic background, and cultivation management and therefore by the organic production system [17]. In particular, the limited and intermittent availability of nutrients, particularly nitrogen, could notably lead to influencing the tuber quality profile [18].

This review, based on the most relevant scientific literature, discusses the contemporary state of knowledge on crop nutrition and soil fertility management in organic potato crop production and how these can affect tuber yield and quality. Side-by-side comparative studies were considered, including both organic and conventional farming practices or studies in organic potato systems; however, on occasion, research conducted in integrated or sustainable potato crop systems with the aim of including information that could be utilized in organic farming was also taken into consideration. In conducting the literature search for this review, the authors adopted various strategies, focusing on reputable journals indexed in databases such as Scopus, Web of Science, PubMed, and Google Scholar, with publications dated after 2000. Articles were selected based on their relevance to the topic. Overall, it is noted that there is a preponderance of papers on the effects of fertilization in potato organic farming on tuber yield, rather than on tuber quality (Figure 1); however, it is interesting to note that papers on both tuber yield and quality have shown an almost continuous growth trend from 2000 to the present, demonstrating the interest of researchers worldwide in this topic.

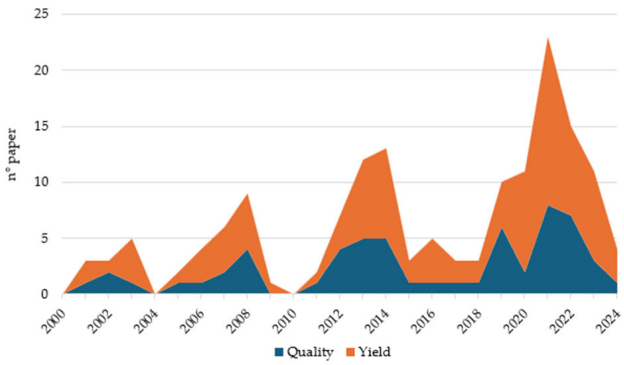


**Figure 1.** The number of scientific publications per year from 2000 to 2024 indexed in Scopus® database using the keywords "organic farming potato tuber quality" in blue and "organic farming potato tuber yield" in orange.

## 2. Crop Nutrition and Soil Fertility Management in Organic Potato

In organic potato production, maintaining proper soil fertility is paramount due to the crop's high nutritional demands. Although there is no worldwide regulation governing

the use of organic fertilizers, the European Union (EU) has implemented a legal framework that outlines the permitted organic fertilizers, soil conditioners, and nutrients for use in EU organic production. These are detailed in Annex 1 of Regulation (EU) 2018/848 [19]. Following the regulation, organic potato production practices in Europe are based on the principle that no synthetic chemical compounds are applied. This means that organic producers need to adopt different approaches to maintaining soil fertility and plant health, including the following:

- Crop rotation;
- Cultivation of nitrogen-fixing plants and other green manure crops to restore the soil fertility;
- Choosing resistant varieties and breeds and techniques that encourage natural pest control.

Fertility management inputs, such as fertilizers and soil conditioners, should be used only if they adhere to the principles and objectives of organic production, with a strict limitation on the use of chemically synthesized inputs. Within this conceptual-regulatory framework, the recycling of wastes and by-products from plant and animal sources is essential for replenishing nutrients and organic carbon (C) in soils. Organic amendments such as manure and compost are essential for managing soil fertility and promoting the long-term sustainability of crop production. Numerous studies have demonstrated that organic inputs improve soil structure, enhance water retention, support root growth, and boost microbial activity [20]. To mitigate the risk of nitrate contamination, EU Regulation 2018/848 [19] imposes a restriction on the total amount of organic nitrogen that can be applied in organic farming, capping it at 170 kg $ha^{-1}$ $year^{-1}$. This limit includes different types of organic materials, such as farmyard manure, dried manure, chicken manure, composted manure, solid animal waste, and liquid animal waste.

The chemical composition of the different organic products that are used for crop nutrition and to maintain soil fertility in organic farming can vary greatly. Table 1 reports a summary of the average nutrient content of the most common organic products applied for fertilization in organic potato crops.

**Table 1.** Summary of the average nutrient content of some organic products (adapted from Gelaye) [21].

| Organic Products | Nutrient Content (%) | | |
|---|---|---|---|
| | N | $P_2O_5$ | $K_2O$ |
| Farmyard manure | 0.5–1.5 | 0.2–0.4 | 0.5–1.0 |
| Crop residues | 0.34–0.63 | - | 1–6 |
| Organic waste | 3.03 | 2.63 | 1.4 |
| Green manure | 40–60 | 2.5–6.55 | 0.0327 |
| Vermicompost | 2–3 | 1.55–2.25 | 1.85–2.25 |
| Compost | 2 | 0.5–1 | 2 |
| Biogas slurry | 1.4–1.8 | 1.1–1.7 | 0.8–1.3 |

In addition to macronutrients such as nitrogen (N), phosphorus (P), and potassium (K), organic products also have micronutrients such as copper (Cu), manganese (Mn), and zinc (Zn). In organic farming, managing fertilization is challenging primarily because nitrogen is supplied indirectly through organic fertilizers, which must undergo mineralization to release mineral nitrogen into the soil [8,11]. Synchronizing the nitrogen supply from these fertilizers with the nitrogen demands of potato crops is often difficult. This synchronization depends on the chemical composition of the organic fertilizers, particularly their nitrogen content and C/N ratio, as well as on the pedo-climatic conditions that influence the decomposition and mineralization of organic matter. Effective nitrogen management, therefore, requires a thorough understanding of the mineralization processes associated with the organic fertilizers being used, ensuring that nitrogen release aligns with the potato crops' peak nitrogen demand periods [22]. In this context, Harraq et al. [23] evaluated nitrogen mineralization and release from various organic fertilizers used in organic farming.

Their study involved incubating four commonly applied organic fertilizers—worm compost (5 t ha$^{-1}$), compost (5 t ha$^{-1}$), sheep manure (30 t ha$^{-1}$), and fishmeal (3.5 t ha$^{-1}$). The highest nitrogen mineralization apparent rates (NMAR) were found to be 62.3% for fishmeal, 38% for compost, 30% for worm compost, and 18% for sheep manure. By the end of the incubation, nitrogen immobilization was observed in both worm compost and compost, attributed to an increase in the C/N ratio.

The present review summarizes the results of the research carried out in organic potatoes to evaluate the effects on the yield and tuber quality attributes deriving from the use of organic products for crop nutrition and soil fertility distinguished in animal manures, green manures, organic amendments, and biostimulants. Figure 2 summarizes the most studied organic products for nutrition and fertility management in organic potatoes.

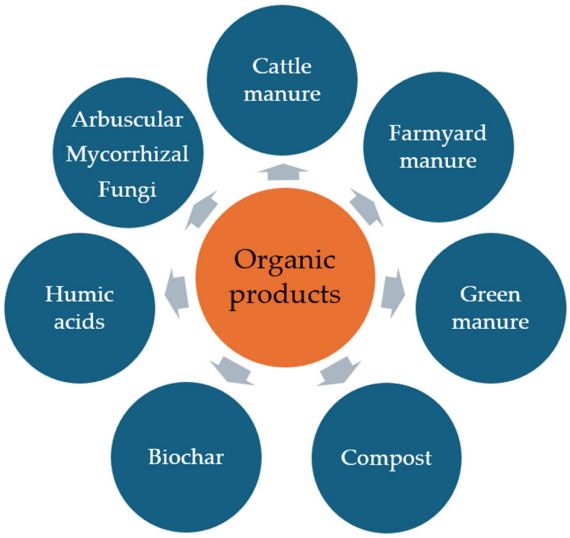


**Figure 2.** Most common fertilizers, amendments, and biostimulants studied in organic potato systems.

## 3. Animal Manure in Organic Potato Cultivation

The main animal-derived fertilizers used in potato organic production include poultry, pig, sheep, and cattle manure, along with urine. The utilization of these fertilizers depends on factors such as regional availability, cost, transportation, and handling. Although manures are not sufficient nitrogen sources for achieving maximum potato yields, they do contribute to increasing soil organic carbon levels. Additionally, applying organic manure enhances soil fertility and structure, fostering a more stable ecosystem by supporting soil fauna and flora [24]. Farmyard manure (FYM) consists of a decomposed mixture of animal waste, including dung, urine, litter, and leftover roughage and feed provided to the animals [25]. When fully decomposed, FYM serves as an excellent source of organic carbon, which supports the biotic activity of soil flora and fauna [26]. FYM also has all the macro-and micronutrients needed for plant development including potatoes, playing an important role in organic farming systems for crop nutrition and soil fertility maintenance [27]. However, some researchers have highlighted limitations associated with the use of manure in organic agriculture, particularly in optimizing multiple nutrients for potato crop nutrition [28]. The yield gap between organic and conventional potato systems associated with fertilization seems mainly due to the lower supply/availability of N from FYM compared with NPK mineral fertilizers [29]. Rempelos et al. [30] supported these results by the finding of lower leaf chlorophyll and tuber N content in FYM-fertilized potato crops, although results suggest that K was the main macronutrient limiting yield. In any case, it is very difficult to envisage approaches/strategies that may close the yield gap associated with fertilization, because the maximum manure inputs for organic crops allowed in a given year under EU environmental legislation for nitrate-sensitive zones are equivalent to 170 kg N ha$^{-1}$. Hajšlová et al. [31] investigated the effects of organic versus

conventional farming on potato quality. The field trials were conducted from 1996 to 1999 in two different locations in the Czech Republic, involving eight potato cultivars: Christa, Koruna, Krystala, Rosara (very early maturing), Krasa and Monalisa (both early maturing), and Karin and Rosella (both semi-early maturing). Crop rotation and organic farmyard manure at a rate of 40–45 t $ha^{-1}$ were employed in the organic system fields. The authors reported significant differences between the farming systems in terms of tuber yield and tuber size distribution, but tuber dry matter (−5% in conventional tubers) and starch content were not significantly influenced, in accordance with the findings of Herencia et al. [32]. Additionally, no significant effects were observed on tuber micronutrient contents (B, Fe, Mn, and Zn), consistent with the results of Warman and Havard [33]. Among other parameters characterizing the nutritional profile of tubers, the ascorbic acid content varied from year to year and was only significantly influenced by the farming system in individual years. Conversely, chlorogenic acid, the most abundant phenolic acid in potato tubers, increased by 45% in organically grown tubers, despite significant year-to-year variation. Makaraviciute [34] studied the effect of organic (manure) and mineral fertilizers on the yield and quality of different potato varieties. It was found that the highest potato tuber yields of all the tested varieties were harvested when one-component and complex mineral fertilizers with microelements had been applied, while the lowest when manure (60 t $ha^{-1}$) had been used in spring. Makaraviciute also reported non-significant differences in potato content in essential amino acids between organically and conventionally grown potato tubers [34].

Wszelaki et al. [35] evaluated mineral and glycoalkaloid concentrations in organically (fertilized with composted dairy manure, 6.5 Mg $ha^{-1}$) and conventionally (fertilized with mineral 10-20-20 N-P-K, 672 kg $ha^{-1}$) grown redskin potatoes. They found that in tuber skin and flesh, potassium, magnesium, phosphorus, sulfur, and copper concentrations were significantly higher in the organically grown potatoes, while iron and manganese concentrations were higher in the skin of conventionally grown potatoes. In addition, glycoalkaloid levels tended to be higher in organic potatoes.

Bártová et al. [36] on five cultivars in two localities during three consecutive years, compared organic (fertilized with farmyard composted dairy manure, 40 t $ha^{-1}$), to conventional (fertilized with common manure, 40 t $ha^{-1}$ + mineral fertilizers: 100 kg $ha^{-1}$ of N, 35 kg $ha^{-1}$ of P and 60 kg $ha^{-1}$ of K) cropping systems. They found that organically produced potato tubers contained a significantly lower content of total nitrogen, crude protein, nitrates, and glycoalkaloids ($\alpha$-solanine and $\alpha$-chaconine). Paffrath and Milz [37] conducted field trials, during 2005–2007, to test the effects of organic fertilization, pregermination, and copper treatment on tuber quality and yield performance of the early maturing cultivar Princess. Fertilization with organic nitrogen reduced the starch content of the tubers in the first year of trials; however, this effect was not observed in the subsequent two years, with starch levels remaining comparable to those of non-treated control. Conversely, copper treatment was reported to significantly increase starch levels in the tubers, with an average increase of 7–15% compared to the control group over the three-year period. In a field trial conducted in Italy [38] with two potato cultivars (Agria and Merit), the organic farming system (using an organic mix of manure, feathers, and torrefied bone-meat, 6% N) was compared to conventional farming systems (using ammonium nitrate, 33% N). It was found that organic farming caused a 25% marketable yield reduction with a higher percentage of large tubers under conventional farming; organic potatoes had higher dry matter content, reducing sugars and total protein than conventional ones. A study conducted in Italy [39] compared the performance of three potato cultivars over two seasons under organic and conventional cultivation systems. The organic system used a combination of feathers, torrefied bone and meat meal, dried manure, and hydrolyzed pelt, while the conventional system relied on ammonium nitrate. The results showed that the organic system consistently produced lower total yields compared to the conventional system in both years. However, during the second season, when late blight infection was less severe, the yield gap between the two systems decreased, varying between 7% and 20%

depending on the cultivar. In addition, the efficacy of animal-based bio-fertilizers was highlighted in enhancing the total phenolic content of potatoes. In addition, they observed an improved sensory performance after frying, with increased crispness and a lower degree of browning; these organically fertilized potatoes had a lower nitrate content compared to conventionally grown ones, a characteristic that is beneficial for human health, as previously confirmed [40]. Lombardo et al. [41] evaluated the mineral profile in organically (mixture of feathers and torrefied bone and meat meal plus a mixture of dried manure and hydrolyzed pelt) and conventionally (100 kg $ha^{-1}$ N, 70 kg $ha^{-1}$ $P_2O_5$ and 150 kg $ha^{-1}$ $K_2O$ + 83 kg $ha^{-1}$ N in the form of ammonium nitrate) grown potatoes. Specifically, the organically grown potatoes exhibited higher phosphorus content, even though lower levels of potassium, calcium, sodium, iron, and manganese [41]. In a three-season field trial, organic vs. conventional was compared on five potato genotypes [42], utilizing for fertilization (100 kg $ha^{-1}$ N, 70 kg $ha^{-1}$ $P_2O_5$, and 150 kg $ha^{-1}$ $K_2O$), respectively, a mixture of feathers and torrefied bone and meat meal (organic) and NPK synthetic fertilizer (conventional). The organic cultivation system was less productive than the conventional one across the 3 seasons (−5% season I, −50% season II, and −25% season III), due to lower availability of N and to the appearance time and severity level of late blight infection. A different behavior of genotypes was also found. Grudinska et al. [43] on 4 potato cultivars in experimental fields, studied organic (Manure–28 t $ha^{-1}$ + mustard as a catch crop) and conventional (4–5 t plowed rye straw + 1 kg mineral nitrogen per 100 kg straw + mustard as a catch crop; N: 100 kg $ha^{-1}$, P: 53 k $ha^{-1}$, K: 150 kg $ha^{-1}$) fertilization management over two years. They found higher total phenolic content in potato tubers under organic production than in potatoes grown conventionally. Kazimierczak et al. [44], in a controlled field experiment in Poland, evaluated the concentrations of polyphenols, lutein, vitamin C, and nitrates in eight potato cultivars grown organically (fertilized with Manure–28 t $ha^{-1}$ + mustard as a catch crop) and conventionally (fertilized with 4–5 t plowed rye straw + 1 kg mineral nitrogen per 100 kg straw, N: 100 kg $ha^{-1}$, P: 53 kg $ha^{-1}$, K: 150 kg $ha^{-1}$). Higher concentrations of nitrates and lutein were found in conventional compared to the organic tubers, while organic potatoes were, on average, richer in phenolic compounds. Keutgen et al. [45], in three consecutive years and on 10 genotypes, evaluated organic (fertilized with 25 t $ha^{-1}$ composted manure) compared to integrated production system (fertilized with 120 N, 60 $P_2O_5$, 180 $K_2O$ + 15 t composted manure + foliar fertilization Adob Cu, Adob Mn, Adob S, Basfoliar 36 Extra, or green manures + 90 N, 110 $P_2O_5$, 180 $K_2O$). They found higher contents of phenolic compounds, flavonoids, and ascorbic acid in organically grown potato tubers than the conventionally grown potato tubers. Shafeeva et al. [46] studied the impact of cattle manure on potato yields and the quality of the tubers grown under both irrigated and non-irrigated conditions, in the southern forest-steppe region of the Republic of Bashkortostan. Farmyard manure 40, 60, 80, 100, and 120 t $ha^{-1}$ was introduced in spring, during soil treatment. However, it was found that slightly lower application rates, specifically 100 t $ha^{-1}$ in non-irrigated conditions and 40 t $ha^{-1}$ under irrigation, yielded a higher percentage of marketable tubers. The use of cattle manure, also, influenced the quality of potato tubers: the highest starch content was observed with the application of 120 t $ha^{-1}$ of manure. Additionally, the dry matter content of the tubers was affected by manure, with the highest levels observed at 40 t $ha^{-1}$ in non-irrigated conditions and 100 t $ha^{-1}$ under irrigation, while nitrate levels in the study were under the established safe limits. Haase et al. [47] investigated the impact of N and K fertilization, preceding crop, pre-sprouting, and cultivar on the quality attributes of organically grown potatoes destined for processing into French fries or crisps during two years at two sites. The fertilization treatments consisted of the following: cattle manure (considered as the reference for potassium and nitrogen content), potassium sulfate (40% K), potassium sulfate combined with horn grits, horn grits alone (14% N), and a control treatment with no fertilizer. The cultivars used in the study were Agria and Marlen, both tested as French fries and crisps. Regardless of the other factors under study, it was found that in the first year, the fry color values for fries from crops treated with cattle manure were significantly lower

than those from the control group with no fertilizer. In the second year, however, cattle manure application resulted in significantly higher fry color values compared to those from crops treated with pure horn grits. Ierna et al. [48] investigated the effects of organic versus conventional cultivation on the quality of early potato tubers over two seasons. Their findings, consistent with a previous report [49] indicated that the use of a mixture of meat and bone meal and dried manure in organic farming produced tubers with more attractive skin color, greater skin thickness and firmness, and higher dry matter and total phenolics content. However, these organically grown tubers exhibited lower ascorbic acid content and antioxidant activity compared to conventionally grown tubers. Considering the effects of the cultivation system on the visual appearance and sensory profile of cooked tubers, the same authors reported that organically grown early potato tubers, cultivated with dried manure and animal-based fertilizer, exhibited improved skin appearance and enhanced sensory traits when boiled, fried, and baked [50].

As a rule, the availability of nitrogen present in organic manures is very low (about 3.0%) compared to inorganic fertilizers, and this is the reason why animal manures generally fail to satisfy the nitrogen needs of the potato. Many experimental works have demonstrated that the addition of minerals to organic fertilizers, especially of animal origin, improves production performances considerably. In an experimental plot at the University of La Laguna, Tenerife, Spain over two years [51] treatments of fertilizing were evaluated on cv. Cara with a single supply or binary combinations of commercial, farmyard manure, sheep manure compost, ammonium nitrate, and "multicote" (17-17-10 NPK commercial coated fertilizer). Fertilizer rates were determined to supply 168 kg of N $ha^{-1}$, in accordance with normal rates of N used by farmers; each fertilizer of binary combinations supplied 50% of N. Potato yields were similar in all the treatments during the first year of cultivation, although in the second year potatoes that received ammonium nitrate, "multicote", sheep manure compost plus "multicote" or farmyard manure plus "multicote" gave significantly higher yields than those subjected to the other treatments. Peñaloza Monroy et al. [52] carried out a field trial to evaluate the response of three levels of chicken manure (2, 3, 4 t $ha^{-1}$) added to an inorganic fertilization treatment (154 N, 356 P, 60 K) in four potato cultivars. The results showed that the cv. Rosita and Ágata in 4 t $ha^{-1}$ of chicken manure, had more stems and greater fresh weights of foliage and produced the highest tuber yields. In the long-term experiment in a four-course crop rotation, Baniuniene & Zekaite [53] studied the effects on potatoes of cultivation with and without farmyard manure (40 t $ha^{-1}$) combined with various mineral fertilization ($N_0P_0K_0$; $N_{90}P_{90}$; $P_{90}K_{120}$; $N_{90}K_{120}$; $N_{90}$ $P_{90}K_{120}$). The long-term experimental data suggest that farmyard manure (FYM) increased potato tuber yield by 35–82%, depending on fertilizer combinations. Mineral fertilizer efficacy on the background without FYM was up to 28% higher. The highest tuber yield increases were obtained by using fertilizer combinations with nitrogen. Potato crops applied with only mineral fertilizers contained higher starch and dry matter contents in tubers compared with those applied with FYM and mineral fertilizers. Fertilizer combinations with potassium tended to reduce starch and the dry matter content in tubers. Caliskan et al. [54] in a field experiment conducted at Hatay, Turkey, studied the effects of farmyard manure (0, 10, 20, 30, 40, and 50 t $ha^{-1}$) and mineral fertilization (no or 200-90-90 kg $ha^{-1}$ N-P-K, respectively) on the growth and yield of early potato crops. The application of farmyard manure had positive effects on growth and yield with or without mineral fertilization. Tuber yield increased as the farmyard manure levels increased under non-mineral fertilized conditions while no significant increase was obtained from 40 and 50 t manure $ha^{-1}$ rates in mineral-fertilized plots. The application of farmyard manure significantly increased the dry-matter content of tubers, and this was more evident in mineral fertilized plots. Other researchers have also explored the impact of nutrient supply and management on potato production. For instance, researchers found that a combined application of farmyard manure (FYM) at 18.75 t $ha^{-1}$ and NPK (25:25:25 kg $ha^{-1}$) significantly improved total tuber yield [55]. Similarly, the joint use of 40 t of FYM and 300 kg of nitrogen fertilizer resulted in the highest total dry weight, plant height, and dry matter content. Additionally, the maximum

average tuber weight and yield were obtained from 40 t of FYM and 200 kg of nitrogen fertilizer [56]. In India, investigations into the effects of nitrogen and FYM on potato productivity, nutritional content, and quality revealed positive responses to increasing rates of both FYM and nitrogen fertilizers [57]. This response may be attributed to enhanced metabolite synthesis. Furthermore, the combined application of 24 t of FYM per hectare and 180 kg of nitrogen per hectare yielded the highest tuber production. Interaction effects between FYM and nitrogen fertilizers consistently outperformed separate applications. A study conducted in Jimma District, Ethiopia, in 2016 assessed different rates of organic and inorganic fertilizers on potato growth and yield components. The combined use of 20 t $ha^{-1}$ of FYM and 70 kg $ha^{-1}$ of nitrogen fertilizer resulted in the largest plant and leaf diameter [58]. In another Ethiopian study, the potato cultivar 'Jalene' was subjected to a combined experiment involving farmyard manure (ranging from 0 to 20 t $ha^{-1}$) and nitrogen (at rates of 0, 35, and 70 kg $ha^{-1}$). The results demonstrated that the interaction between different levels of farmyard manure and nitrogen significantly influenced various parameters, including leaf area, plant height, leaf length, leaf number, leaf diameter, stem diameter, and stem number. Notably, the control treatment exhibited the minimum values for all these parameters [59]. Furthermore, a 2020 study conducted in the North Shewa Zone of the Amhara Regional State in Ethiopia aimed to assess the impact of farmyard manure (FYM) at rates of 0, 4.5, 9, and 13.5 t $ha^{-1}$, along with inorganic fertilizers at rates of 0, 81.7, 163.4, and 245.1 kg $ha^{-1}$, on the growth and yield of irrigated potatoes. The results indicated that the combined application of 245.1 kg $ha^{-1}$ of inorganic fertilizers with 13.5 t $ha^{-1}$ of FYM resulted in the highest marketable and total tuber yields [60]. Atanaw and Zewide [61], in a paper on the effect of the combined application of inorganic nitrogen, phosphorus, and potassium (NPK) and cattle manure fertilizers on vegetative growth, yield components, and improved productivity of the soil, claimed that animal manure such as cattle manure has positively beneficial effects on vegetative growth, yield, and tuber quality. Therefore, a combined application of mineral NPK and cattle manure is essential to sustain high yields, better tuber quality, and more profit, as well as to improve soil fertility.

## 4. Green Manure in Organic Potato Cultivation

Green manuring consists of incorporating green plants into the soil, either by cultivating them in the same field (cover crops) or by using plants that were grown elsewhere at the green stage just before flowering. Researchers suggest intercropping green manure with potatoes as a complementary crop, as it has the potential to enhance crop productivity and improve soil fertility [62,63]. Utilizing cover crops plays a multifaceted role in organic agriculture by maintaining soil organic matter, enhancing soil health, mitigating erosion, and optimizing nutrient management, thereby increasing nutrient availability [64]. In organic potato agro-ecosystems, a variety of cover crop families and species have been introduced to provide different services based on the characteristics of the agro-ecosystem. Generally, non-leguminous cover crops such as sunflower, crucifers, and cereals such as rye and barley, offer benefits such as organic matter generation, weed suppression, and erosion control. Non-leguminous cover crops can also function as nitrogen (N) catch crops, optimizing N utilization throughout the rotation system (e.g., rye) [65,66], and capturing N that might otherwise leach from the soil [67]. Furthermore, certain non-leguminous cover crops such as winter rye, ryegrass, brassicas, and buckwheat, have demonstrated the ability to reduce soil-borne diseases when incorporated into rotations with potatoes [68]. On the contrary, leguminous crops can serve as full-season cover crops either with a cereal nurse crop (e.g., small red clover undersown in oats, barley, or wheat) or as the sole cover crop in the year preceding potatoes. These crops are typically terminated as green manures, with estimates suggesting that the impact of a preceding leguminous cover crop is comparable to applying N fertilizers at a rate ranging from approximately 20 to 150 kg N $ha^{-1}$ [69]. It is widely acknowledged that the release of N from decomposing green manure residues can coincide well with plant uptake, potentially enhancing N uptake efficiency and crop yield while mitigating N leaching losses [70]. For these reasons, leguminous

cover crops play a crucial role in the fertility management of organic potato farming, replacing chemically synthesized nitrogenous fertilizers and being particularly beneficial when preceding potatoes, which have high N requirements [71]. Uchino et al. [72] evaluated the effect of fertilization and inter-seeding cover crops on the growth of main crops and weeds and the stability of weed suppression under four-year rotational organic farming. Fertilization involved a fully ripened compost (N: 0.725%, $P_2O_5$: 0.59%, $K_2O$: 0.86% *w*/*w* in fresh weight) at 45 t $ha^{-1}$ on average over the 4 years of study and 1 t $ha^{-1}$ of fermented organic fertilizer (N 5%, $P_2O_5$ 6%, $K_2O$ 4%). In an organic farming system, researchers interseeded two cover crops—winter rye (*Secale cereale* L.) and hairy vetch (*Vicia villosa* Roth)—in furrows alongside potato (*Solanum tuberosum* L.), soybean (*Glycine max* Merr.), and maize (*Zea mays* L.). The study revealed that effective and stable weed suppression could be achieved without compromising the yield of main crops when cover crops were interseeded with adequate fertilization.

The choice of cover crop species is crucial, as demonstrated by a separate investigation conducted in Central Italy (Viterbo) over a two-year period, which examined yield and weed control effects in potato crops following different cover crops [73]. In a three-year chick-pea/potato/tomato rotation, each crop was preceded by seven different soil managements: five cover crops (rapeseed, Italian ryegrass, hairy vetch, snail medick, and subclover), one unfertilized weedy fallow (cover crop absent), and one control (weedy fallow fertilized with mineral N at a rate of 170 kg $ha^{-1}$ for potato). Two different weed control regimes in potatoes were also applied [weed-free crop (1 inter-row hoeing + 1 hilling up + manual weeding on the row); mechanical control (1 inter-row hoeing + 1 hilling up)]. The potato crops following the cover crops were only fertilized with green manure. Following subclover and hairy vetch the potato crop yield was similar to that obtained by mineral N-P-K fertilization. In a study conducted by Larkin and Halloran [74], researchers evaluated potential disease-suppressive crops using four different production management approaches: cover crop, green manure, harvested crop-residue-incorporated, and harvested crop-residue-not-incorporated. These trials were part of potato rotation experiments, and the focus was on their impact on yield. Mustard blend, sudangrass, and rapeseed rotations led to yield increases (ranging from 6% to 11%) compared to a simple rotation control. Notably, all rotation crops managed as green manures consistently achieved higher yields (6% to 13%) than other management practices. Among them, the combination of mustard blend managed as a green manure was particularly effective, resulting in a 25% yield increase relative to a soybean cover crop.

In a field experiment by Tein et al. [29], potato (*Solanum tuberosum* L.) was part of a five-crop rotation in which red clover (*Trifolium pratense* L.), winter wheat (*Triticum aestivum* L.), peas (*Pisum sativum* L.), potato and barley (*Hordeum vulgare* L.) followed each other simultaneously on the same field. The field experiment was performed with six different farming systems as follows: two organic and four conventional. In both organic farming systems, catch crops were used to provide organic green manure; in the second organic system, fully composted cattle manure at a rate of 40 t $ha^{-1}$ was also added as a fertilizer. The four conventional farming systems differed in the amounts of mineral fertilizers used as follows: $N_0P_0K_0$ (control), $N_{50}P_{25}K_{95}$ (low), $N_{100}P_{25}K_{95}$ (average), or $N_{150}P_{25}K_{95}$ (high). Fresh tuber yields were significantly lower under organic systems than conventional. However, the other organic system, involving green manure and composted cattle manure, significantly increased the average soil organic carbon (C) and phosphorus (P) concentrations after potato cultivation, whereas the conventional system that received mineral nitrogen fertilizers showed fluctuations in soil nitrogen (N) total concentration, average soil organic C and P concentrations, the soil pH and potassium after potato cultivation and magnesium (Mg) concentrations in relation to N dose of fertilizer. Tein et al. [29] reported that integrating potatoes into a three-year crop rotation experiment with red clover (*Trifolium pratense* L.), winter wheat (*Triticum aestivum* L.), peas (*Pisum sativum* L.), and barley (*Hordeum vulgare* L.) was beneficial also for potato quality. Indeed, the average P concentrations were higher in organic potato tubers compared to other systems, while

the Mg content in organic tubers was surpassed only by the treatment involving organic farming systems supplemented with fully composted cattle manure. In a study by Nyamdavaa and Friedel [75], the impact of different preceding crops, cover crops, and manure application on the agronomic performance of potatoes was investigated over two consecutive years in an organic farming system. The experiment evaluated lucerne, field pea, and spring barley as pre-crops, non-leguminous species, and a mix was applied as a cover crop (a bare fallow treatment was adopted as a control in comparison to cover crop) along with farmyard manure application. Notably, the subsequent crop response to preceding crops was minimal, with no significant difference in tuber yields (fresh tuber, marketable, and dry matter) observed between legume pre-crops and barley. However, both cover crops and manure slightly increased tuber dry matter yield in the first year, while the second year showed no effect on dry matter yield. Interestingly, the percentage of small-sized tubers (<35 mm in diameter) increased notably in the second year compared to the first. Additionally, cover crops used as green manures contributed to a higher percentage of large-sized tubers (>65 mm in diameter) over the two-year period. In a study conducted in the highlands of Awi Agro-Ecological Zone [76], two rotation systems and four levels of organic treatments: V1 = 0 t $ha^{-1}$ farmyards manure (FYM), V2 = 2.5 t $ha^{-1}$ fresh sesbania green manure (FSB), V3 = 5 t $ha^{-1}$ FYM, and V4 = 5 t $ha^{-1}$ FYM +2.5 t $ha^{-1}$ FSB were factorially arranged in fixed plots for three years. Among all, the highest total potato tuber yield was obtained at the combined application of 5 t $ha^{-1}$ FYM +2.5 t $ha^{-1}$ FSB. The treatment combination increased total potato tuber yield by 140% and 41% over that of the first and the second years. The effect of cover crops plus added composted manure was also studied on the soil microbial hydrolytic activity [77]. A study investigated the impact of five-field crop rotations within two distinct farming systems: organic (Org II, which included winter cover crops and composted manure, compared to Org 0 as the control) and conventional (Conv II, which used mineral nitrogen at a rate of 150 kg $ha^{-1}$, compared to Conv 0 as the control) on crop productivity and soil health. After potato cultivation, the lowest and highest decrease in the soil microbial hydrolytic activity was seen in Org II and Conv II systems, respectively. Soil organic carbon (SOC) and total nitrogen (N) levels were found to be higher in organic farming systems, with no significant changes observed after potato cultivation. In a field study conducted on Prince Edward Island [78], researchers examined the impact of applying pen-pack cow (*Bos taurus*) manure at a rate of 20 Mg $ha^{-1}$ and the use of cover crops—comprising grasses, legumes, or a mixture of both—with red clover (*Trifolium pratense* L.) serving as the control, on nitrate dynamics, soil nitrogen supply capacity, and subsequent potato yields. On average, red clover accumulated 88% more total nitrogen than the grass-legume mixtures; however, this did not lead to higher potato yields. In contrast, pearl millet and sorghum sudangrass (*Sorghum bicolor* and *Sorghum bicolor* var. Sudanese) were associated with lower soil nitrate levels compared to red clover but resulted in higher total potato yields. The incorporation of manure increased both total and marketable yields by 28% and 26%, respectively, and enhanced soil nitrogen supply capacity by an average of 44%. Rittl et al. [79], in a field with regular potato growing, examined the effects of different organic amendments with or without winter rye as a cover crop. They found that the cover crop did not affect soil organic matter, but increased tuber yields in the second year, and reduced the severity of potato diseases by 10% in post-harvest potatoes in both years. The use of cover crops and manure in organic farming can produce comparable outcomes to those of conventional farming with low nitrogen input, as also demonstrated by the research results of Margus et al. [80]. In their study conducted in Estonia from 2018 to 2020, potato crop performances under three organic (Org) and four conventional ($N_0$, $N_{50}$, $N_{100}$, $N_{150}$) system treatments were assessed. The crop rotation sequence included spring barley (*Hordeum vulgare* L.) with under-sown red clover, red clover (*Trifolium pra*tense L.), winter wheat (*Triticum aestivum* L.), pea (*Pisum sativum* L.), and potato (*Solanum tuberosum* L.). The organic farming system included three treatments: Org I (organic control), Org II (organic crop rotation with winter cover crops), and Org III (organic crop rotation with winter cover crops and supplemented with composted cattle

manure). Over the three-year trial period, conventional systems showed an average yield that was 25% higher than that of organic systems. However, yields within the organic systems demonstrated greater stability. The Org I treatment achieved the same dry matter yield as the $N_0$ system, indicating that the application of chemical plant protection without fertilization did not yield any positive effect on growth. Annually, the yield in the Org III system was equivalent to that of the $N_{50}$ system. There were no significant differences in the number of tubers per plant across the different farming systems, though notable differences were observed between the trial years. Tubers from conventional systems had a lower starch content compared to those from organic systems. Mamiev and colleagues [81] conducted a comprehensive study to improve crop productivity and quality using green manure crops, manure, and mineral fertilizers while enhancing soil fertility. In the foothill zone of North Ossetia-Alania, green manure improved the bulk density, porosity, and air capacity in the arable soil layer and consequently increased moisture content in the 0–30 cm soil layer. Over a three-year period, the combined use of straw, nitrogen fertilizers, and green manure resulted in the highest potato yield, with an increase of 34.0%, compared to the control and also improved tubers quality, with increases in dry matter content, starch, and vitamin C. A three-year organic crop rotation was set up in a field with sandy loam soil, with a cover crop of rye and vetch grown over the three autumn/winter seasons for green manure, followed by potato and lettuce (first year), Swiss chard and turnip (second year), and Portuguese cabbage and carrot (third year) [82]. Nitrogen (N) mineralization was determined by field incubation in response to green manure (GM), with 20 and 40 t $ha^{-1}$, farmyard manure (FYM) (C20 and C40), and GM with 1 and 2 t $ha^{-1}$ of commercial organic fertilizer (CF1 and CF2). The second season crops (lettuce, turnip, and carrot) yields were higher for the treatment C40 compared to all other treatments because most of the commercial fertilizer was mineralized during the previous crop. Swiss chard, grown in a short season (54 days), produced a higher yield for CF2 compared with C40. However, this was not true for potatoes (first year), probably because of increased manure mineralized N recovery during the longer growing season for the potatoes (124 days), nor for the cabbage (third year), which had a short growing season (56 days), because of increased N availability with continuous composted and green manure application. This study highlighted that field incubation can be used to assess mineralization rates and that the fast N release of commercial fertilizers increased the yield of the first crop of the year, whereas the slowly released N of FYM increased the yield of both crops of the year, with lower risk of N loss. In a study by Drakopoulos and colleagues [83,84], the effects of different organic amendments (solid cattle manure, lucerne pellets, and grass/clover silage) on crop performance and nitrogen utilization in organic potato cultivation were examined. Notably, plant-based fertilizers demonstrated improved nitrogen utilization compared to animal-based manures, and lucerne pellets consistently yielded the highest crop output, irrespective of tillage practices. A study conducted at the Intermountain Research and Extension Center in Tulelake examined the impact of cover crops and organic amendments (including composts, manures, bloodmeal, and soymeal) on soil nitrogen availability for potato production. The research evaluated various cover crop species, three planting dates, and multiple cover crop combinations [85]. Notably, vetches and field peas, when used as green manure, effectively met the in-season nitrogen requirements of potatoes. These cover crops, whether grown individually or in mixtures with non-legume species, yielded potato crops comparable in quality and yield to those cultivated using conventional fertilizers.

## 5. Organic Amendments in Organic Potato Cultivation

The incorporation of organic amendments is a common practice in organic potato production systems [86]. Organic amendments such as compost, vermicompost, and biochar are considered to be soil conditioners rather than a source of nutrients, and their release of mineral elements, mainly nitrogen, is thus limited. They genuinely could improve soil fertility, physically, chemically, and biologically. Physically, soil that has been amended with compost or vermicompost has improved aeration, porosity, bulk density, and water

retention; in addition, chemical characteristics including pH, electrical conductivity, and organic matter content are also enhanced [21]. Table 2 reports some examples of applied amendments in organic potato cultivation.

**Table 2.** Impact of different amendments in organic potato cultivation.

| Amendments | Impact on Tuber Yield | Impact on Tuber Quality | Location | References |
|---|---|---|---|---|
| Swine manure-sawdust compost | decrease | | Canada | Lynch et al. [20] |
| Worm-compost | increase | | Morocco | Harraq et al. [23] |
| Compost + green manure | increase | | Italy | Canali et al. [68] |
| Biochar + liquid digestate | - | | Norway | Rittl et al. [79] |
| Food residues + MSWC | increase | | Italy | Passoni & Borin [87] |
| Compost | increase | - | Canada | Carter et al. [88] |
| Compost | increase | | Egypt | El-Sayed et al. [89] |
| Pulp-fiber compost | increase | | Canada | Fahmy et al. [90] |
| Different types of compost | no effect | | Canada | Wilson et al. [91] |
| Compost | | increase phenolics, flavonoids, anthocyanins | Lithuania | Vaitkevičienė et al. [92] |
| On-farm compost (fish waste, seaweed, pine bark) | increase | increase reducing sugars | Spain | Illera-Vives et al. [93] |
| MSWC [1] and paper mill biosolid compost | decrease | | Canada | Alam et al. [94] |
| MSWC | increase | increase micronutrients | Spain | Escobedo-Monge et al. [95] |
| On-farm prepared compost | increase | | Belgium | Willekens et al. [96] |
| Farmyard compost, compost tea | increase | increase dry matter, specific gravity | Egypt | El-Tantawy et al. [97] |
| Conifer-based compost + green manure+ biofertilizer | increase | | United States | Bernard et al. [98] |
| Biochar | increase | | Egypt | Youssef et al. [99] |
| Biochar | increase | | Nepal | Upadaya et al. [100] |
| Biochar, biochar + compost | increase | | Canada | Mawof et al. [101] |
| Biochar + recommended NPK | increase | | Canada | Farooque et al. [102] |
| Biochar + organic fertilizer | increase | | China | Hou et al. [103] |
| Biochar + recommended NPK | increase | increase dry matter, specific gravity | Bangladesh | Mollick et al. [104] |
| Biochar + vermicompost + bonemeal, others | increase | | India | Singh & Siddique [105] |

[1] MSWC = Municipal Solid Waste Compost.

### *5.1. Compost*

Composting stands out as the premier strategy for managing organic solid waste, relying on the bio-oxidative decomposition of original organic materials. This process transforms organic waste into humified, stable, odorless, and pathogen-free material, suitable for enhancing degraded soils. Compost is highly regarded in organic agriculture due to its profitability, environmental friendliness, and ease of handling [106]. The ideal

compost for potato cultivation is open-textured, rich in organic matter, high in nutrients, and neutral in pH. Compost provides a slow-release source of organic nutrients, which can contribute to a nutrient-driven yield response. However, compost degradation occurs slowly, and the amount of nitrogen (N) mineralized from compost in the first year after application is minimal, as evidenced by the crop's very low apparent nitrogen recovery (ANR) [107]. Specifically, compost contains a significant portion of total nitrogen, with over 90% generally not being immediately available for plant uptake [108]. Most of this nitrogen is bound within the organic N-pool, while the mineral nitrogen, which is readily accessible to plants, constitutes less than 2% of the total nitrogen content. Studies have shown that in the year following compost application, the available nitrogen accounts for less than one-fifth of the total nitrogen applied [109]. Consequently, compost alone is insufficient to meet the nitrogen needs of crops in the short term, making it unsuitable as the sole nitrogen source. In their evaluation of nitrogen application through organic amendments in an organic potato field, Lynch et al. [20] observed a decline in tuber yield after applying swine manure-sawdust compost with a C/N ratio of 22, attributing this reduction to nitrogen immobilization. The C/N ratio is a commonly used, though approximate, indicator of net nitrogen mineralization potential. Organic materials with a C/N ratio below 20, which decompose more readily, tend to release nitrogen during decomposition, while those with a C/N ratio above 20 are more likely to temporarily immobilize nitrogen [110]. In a study assessing various composts as nitrogen sources in crop successions, including potatoes and catch crops, Passoni and Borin [87] found that crop response and nitrogen uptake were minimally affected by compost fertilization. On the other hand, Carter et al. [88] reported an increase in tuber yield that exceeded the maximum yield achieved with nitrogen application alone in an experiment exploring the effects of compost on a potato rotation. This "non-nitrogen" compost yield effect was attributed to a slight yet significant enhancement in soil water-holding capacity. In addition, El-Sayed et al. [89] indicated that the organic production of potatoes using 23.8 t $ha^{-1}$ of compost could be an alternative to conventional production with commercial organic fertilizers without significant reduction in yield and quality. In a field experiment conducted at two sites in Atlantic Canada over two years, the impacts of two organic amendments (commercial hog manure–sawdust compost applied at 300 kg total N $ha^{-1}$, pelletized poultry manure applied at 600 kg total N $ha^{-1}$, compared to an unamended control) on Shepody potato yield, quality and soil mineral nitrogen dynamics under organic management were studied [20]. Relatively high tuber yields and crop N uptake were achieved for unamended soil in those site-years when soil moisture was non-limiting. Compost resulted in higher total yields than un-amended control in one of three site-years, although the apparent recovery of N from compost was negligible. Fahmy et al. [90] observed that the addition of pulp-fiber residue compost increased the availability of phosphorus and potassium for potato plants. Specifically, tuber yield improved under supplementary irrigation conditions, while no significant change was noted in rainfed settings compared to unamended plots. The adoption of green manure practices and the recycling of organic materials offer a promising alternative to conventional synthetic fertilizer-based management systems, supporting sustainable potato production without exacerbating potential environmental risks associated with nitrogen leaching [68]. A research study conducted in rain-fed potato production in New Brunswick, Canada, investigated the impact of various compost products on tuber yield and plant nutrient availability. The study included a no-compost control and five compost types: marine with shells compost, poultry manure compost, forestry residues compost, municipal source-separated organic waste compost, and forestry waste and poultry manure compost [91]. In a small plot trial, mature compost products slightly increased plant nitrogen availability, while immature compost led to net nitrogen immobilization. Despite these differences in nutrient availability, there was no significant effect on tuber yield. In on-farm trials spanning 19 site-years, compost did not significantly enhance yield, suggesting that any short-term nutrient benefits from wood waste and manure-based composts are unlikely to impact crop yield. However, there may be potential to reduce nutrient application

rates, particularly for potassium. Vaitkevičienė et al. [92] compared several colored potato cultivars grown organically with 30 t $ha^{-1}$ of compost to those grown conventionally using complex fertilizers (112 kg $ha^{-1}$ nitrogen, 56 kg $ha^{-1}$ phosphorus, and 136 kg $ha^{-1}$ potassium). Their findings indicated that potato tubers cultivated under organic conditions contained higher levels of polyphenols, phenolic acids, chlorogenic acid, p-coumaric acid, caffeic acid, flavonoids, and anthocyanins compared to those grown conventionally.

Illera-Vives et al. [93] investigated the impact of three compost application rates (32 t $ha^{-1}$, 43 t $ha^{-1}$, and 65 t $ha^{-1}$) derived from composted fish waste, seaweed, and pine bark, comparing them to a mineral fertilizer, a certified organic fertilizer made from dehydrated broiler litter, and a control with no fertilizer on potato yield and the chemical composition of potato tubers, petioles, and folioles. The compost showed a strong fertilizing effect, even outperforming the mineral fertilizer. The 65 t $ha^{-1}$ compost treatment increased total production by 53% compared to the control and by 30% relative to the mineral fertilizer. It also performed similarly to dehydrated broiler litter and significantly reduced the proportion of non-commercial potatoes (caliber <35 mm) compared to the control. Notably, only the 65 t $ha^{-1}$ compost treatment altered the tubers' chemical composition by increasing their reducing sugar content.

In Eastern Canada, a five-year study compared four treatments—control, inorganic fertilizer (FERT), municipal solid food waste compost (MSW), and paper mill biosolid compost (PMB)—in organic potato rotations [94]. The study found that soil amendments significantly affected potato yields. Total nitrogen uptake by potatoes was 89, 115, 107, and 147 kg N $ha^{-1}$ for the control, MSW, PMB, and FERT treatments, respectively, with higher uptake levels observed when potatoes followed red clover (119–124 kg N $ha^{-1}$) compared to an oat/pea/vetch mixture (107–108 kg N $ha^{-1}$). Plant nitrogen use efficiency was measured at 299, 263, 263, and 235 for the control, MSW, PMB, and FERT treatments, respectively.

In a study conducted by Escobedo-Monge and colleagues [95], the impact of municipal solid waste compost was compared to other organic and inorganic amendments in terms of potato production, quality, and yield across four potato genotypes. The addition of all amendments, particularly urban waste compost, resulted in raised potato production and elevated levels of macronutrients, micronutrients, and heavy metals in the soil, with a progressive accumulation observed in the tubers.

A long-term fertilization study involving a four-year crop rotation of maize, potatoes, spring barley, and red clover was conducted across two fields, with a one-year offset between them, to assess the impact of various fertilization methods. These included on-farm prepared compost primarily made from vegetable residues (applied in both single and double doses), farmyard manure, slurry, and a combination of slurry with composted municipal waste [96]. In one growing season, potato yields were notably higher for both farm compost treatments, while soil nitrate levels were significantly lower. However, during another season characterized by early, severe, and consistent leaf blight disease pressure, yields were reduced, and the differences between treatments were less pronounced. This study highlighted that using mature compost can promote quicker early-season potato crop development, which is crucial for achieving adequate yields in organic potato farming. A field experiment was conducted (North Nile delta region), to investigate the potential of applying farmyard compost and its compost tea on potato crops (*Solanum tuberosum* L.) [97]. Compared to the control, four application methods (ore compost, compost tea, sediment, and sediment + extract combination) were studied. The application of compost tea enhanced dry shoot yield, fresh tuber yield, tuber dry matter content, crude protein, and tuber-specific gravity in both seasons. Additionally, the combination of sediment and extract significantly increased tuber dry matter and crude protein in both seasons. Incorporating farmyard manure into the soil boosted both total and available nitrogen, phosphorus, and potassium levels in the soil. In organic cropping systems, the synergistic effect of green manure and various organic amendments can significantly enhance soil fertility and yield while also mitigating the risk of nutrient leaching, particularly nitrogen (N) [111,112]. Canali et al. [68] conducted a field experiment in Tuscany, Central Italy, aimed

at evaluating the impact of cattle farmyard manure and compost, applied at three different rates (0, 50, and 100 kg N $ha^{-1}$), in conjunction with a legume green manure cover crop (*Trifolium subterraneum* L.), on potato nutrition, tuber yield, N uptake, and use efficiency. Their findings suggest that eco-functional intensification in organic potato cropping systems can be achieved by leveraging the combined effects of legume green manure and organic amendments. Bernard and colleagues [98] investigated three distinct disease-suppressive management practices. These included a rotation crop of *Brassica napus* (rapeseed) as green manure, compost amendment derived from conifers, and the evaluation of three biological control organisms (*Trichoderma virens*, *Bacillus subtilis*, and *Rhizoctonia solani* hypovirulent isolate Rhs1A1). The study assessed these practices individually and in combination at sites managed under both organic and conventional systems. They found that compost amendment had variable effects on tuber disease. However, the combination of rapeseed rotation and compost amendment consistently improved yield at both sites. Moreover, this integrated approach not only mitigated disease but also enhanced overall crop productivity.

### *5.2. Vermicompost*

Vermicompost is produced through the decomposition process involving various worm species, such as red wigglers, white worms, and other earthworms, resulting in a blend of bedding materials, decaying organic matter, and vermicast. Studies show that vermicompost generally contains higher concentrations of macronutrients and micronutrients than traditional compost, with nutrients such as nitrogen, phosphorus, potassium, calcium, magnesium, and trace elements present in more soluble forms. Moreover, vermicompost offers a beneficial load of enzymatic–bacterial microbes, which provide suppressive and antibiotic effects against pathogens, along with growth-regulating substances and humic acids that enhance plant growth [113]. These characteristics improve soil fertility in physical, chemical, and biological terms, leading to higher crop yields. In a pot experiment, Harraq et al. [23] investigated the impact of applying varying amounts of worm compost (0, 5, 10, and 15 t $ha^{-1}$) and fishmeal (0, 1.75, and 3.5 t $ha^{-1}$) on potato growth and yield. Fishmeal significantly improved leaf number, plant height, dry matter, aerial nitrogen uptake, tuber count, and yield, while worm compost primarily affected leaf number and tuber yield. The optimal yield (554.4 g per plant; 23.1 t $ha^{-1}$) was achieved with a combination of 10 t $ha^{-1}$ worm compost and 1.75 t $ha^{-1}$ fishmeal, resulting in maximum underground and total nitrogen uptake at harvest, supported by nitrogen mineralization apparent rates of 71% for fishmeal and 64.3% for worm compost.

### *5.3. Biochar*

Biochar is a carbon-rich solid produced through the pyrolysis of plant or animal biomass under conditions of limited or partial oxygen. Various feedstocks can be used to produce biochar, including agricultural residues such as rice straw, corn cobs, and wheat residues, as well as animal waste, sewage sludge, municipal solid waste, and biogas residues. The chemical properties of biochar are influenced by the type of feedstock and the processing parameters, such as pyrolysis temperature, heating rate, residence time, particle size, reactor type, and pressure conditions [114]. Due to its unique characteristics, biochar is utilized in various applications, including waste management, adsorption functions, soil amendment in agriculture, catalysis, carbon sequestration, and energy storage. Biochar can enhance fertilizer effectiveness for plant uptake and reduce soil nutrient loss. Nutrient loading onto biochar is crucial for improving fertilizer efficiency, as pristine biochar contains few nutrients [115]. Youssef et al. [99], examined the effect of biochar addition on the production of potatoes grown under sandy soil conditions in integrated farming conditions in Egypt. The study included 12 treatments, which were combinations of three potato cultivars (Accent, Cara, and Spunta) and four biochar application rates (0, 1.25, 2.50, and 5.00 $m^3$/feddan; 1 feddan = 0.42 ha). The results indicated that the potato cultivars Cara and Spunta recorded the highest values for morphological characteristics, leaf content of Ca, Mn, and Cu, as well as tuber yield and quality. The Cara cultivar achieved the

maximum dry weight of various plant parts, the Spunta cultivar exhibited the highest concentrations of photosynthetic pigments in leaf tissues and the greatest starch content in tubers. Conversely, the Accent cultivar displayed the lowest values for these parameters and had the lowest nitrate content in tubers. Upadhyay et al. [100] investigated the impact of various biochar types (including *Lantana camara*, *Ipomoea carnea*, rice husk, and sawdust) on potato growth and yield attributes. Overall, biochar positively influenced total yield. However, even when applied at 0.3% and 1% levels, biochar did not fully prevent the survival or breeding of cyst nematode species in potatoes [116].

In a two-year field study, Mawof et al. [101] evaluated the impact of biochar, compost, and a biochar-compost mixture on soil properties and potato yield when irrigated with wastewater. The treatments included a factorial combination of three levels of barley straw biochar amendment (0%, 1%, and 3%) and two levels of mixed green and kitchen waste compost amendment (0% and 7.5%). Compared to the unamended control, all amendment treatments significantly improved soil physico-chemical properties and crop yield, though they did not affect plant growth or physiological parameters. Soil cation exchange capacity, soil organic matter, and pH were significantly enhanced by compost amendment, with the combination of 3% biochar + 7.5% compost producing some of the best outcomes. In an Atlantic Canada representative soil suitable for potato cultivation, a trial was conducted using 8000 $cm^2$ lysimeters. The study evaluated the impact of four soil amendment treatments: (1) control (no added nutrients), (2) biochar, (3) synthetic fertilizer with recommended NPK, and (4) biochar combined with recommended NPK [102]. The biochar amendment improved soil micro- and macro-nutrients, soil organic matter, pH, and cation exchange capacity (ECE), whereas the maximum potato yield was achieved by the combined application of biochar and synthetic fertilizer. In a combined application experiment [103] involving biochar (B) and organic fertilizer (O) with four concentration gradients using the equal carbon ratio method, it was found that soil fertility was improved by the combined application of biochar and organic fertilizer, with the best effect being achieved at a ratio of B:O = 1:2. When compared to the control, the relative abundance and diversity index of soil bacteria were significantly improved by the treatment at B:O = 1:2. Bacterial diversity directly affected the potato yield, while soil fertility indirectly affected potato yield by influencing the soil bacterial diversity. Mollick et al. [104] conducted a field experiment in Bangladesh to assess the effect of biochar on the yield and quality of potato tubers. The study included nine treatments: a control (no chemical fertilizer or biochar), a recommended fertilizer dose (RFD), a biochar-only treatment, and six combinations of biochar with the recommended fertilizer dose on the Damian cultivar. In general, the combination biochar-RFD significantly increased plant height, tuber weight, tuber yield, tuber dry matter content, tuber-specific gravity, and soil organic carbon when compared to control, RDF, or biochar alone. In a research [105] the impact of biochar-based organic amendment was analyzed on the growth and yield of the potato crop. Different combinations of biochar base organic amendment with recommended doses of fertilizer (RDF), bone meal (BM), vermi-compost (VC), and poultry manure (PM) were studied. Among all the thirteen treatment combinations of biochar base organic amendment, a treatment combination of biochar base organic amendment consisting of 25% RDF + 75% (BM + VC + PM) + 40% Biochar resulted in maximum emergence percentage, plant height, LAI, days to maturity, number of haulm plant-1, average weight of tuber $plant^{-1}$ and tuber yield. Singh et al. [117] investigated the effects of different combinations of biochar, vermicompost, poultry manure, and bone meal on the soil health and quality of the cultivar Kufri Pukhraj, which is widely cultivated in India. Among the various treatments, the combination of a 25% recommended dose of fertilizer with 75% bone meal, vermicompost, and poultry manure plus 40% biochar exhibited the best performance: highest values for pH, electrical conductivity, organic carbon, soil microbial biomass, nitrogen content, labile carbon, and particulate organic carbon. Additionally, this combination achieved the highest starch content and the greatest quantity of A-grade potato tubers. Rittl et al. [79] examined the effects of organic materials: one application of biochar mixed with liquid digestate (BLD), solid

digestate (SD), or farmyard manure (FYM). Organic amendments increased soil organic matter, especially for FYM and BLD, and though they did not affect potato yield or quality, the proportion of marketable potatoes tended to be higher in the amended soil. Worth mentioning is a study carried out in Karangreja District, Indonesia, in which the effects on the quality of potato cultivar Atlantic of three types of charcoal derived from wood, husk, and coconut shell, applied at varying concentrations in addition to commercial organic fertilizer "Petroganik", compared to chemical fertilizers were studied [118]. Regardless of the types of charcoal and concentrations, they found that tubers of organically fertilized plants showed lower moisture content and higher ash content compared to those of chemically fertilized plants.

## 6. Biostimulants in Organic Potato Cultivation

Plant biostimulants are defined as follows: "EU fertilising product the function of which is to stimulate plant nutrition processes independently of the product's nutrient content with the sole aim of improving one or more of the following characteristics of the plant and/or the plant rhizosphere: (1) nutrient use efficiency, (2) tolerance resistance to abiotic stress, (3) quality characteristics, or (4) availability of confined nutrients in the soil or rhizosphere" [119].

Many diverse natural substances and chemical derivatives of natural or synthetic compounds, as well as beneficial microorganisms, are cataloged as plant biostimulants including (i) humic substances; (ii) plant- or animal-based protein hydrolysates; (iii) macro- and micro-algal extracts; (iv) silicon; (v) arbuscular mycorrhizal fungi (AMF); and (vi) plant-growth-promoting rhizobacteria (PGPR) belonging to the genus *Azotobacter*, *Azospirillum,* and *Rhizobium* spp. [120]. Among several plant biostimulants, the most studied in organic cultivation potato systems are the humic substances, Arbuscular mycorrhizal fungi, and biofertilizers.

### *6.1. Humic Substances*

Humic preparations containing humic acids, such as the organic product Rosahumus from Rosier, S.A., offer a promising alternative for soil enhancement. Rosahumus, sourced from leonardites, comprises roughly 85% humic acids and contains notable amounts of potassium (12% $KK_2O$) and iron (0.6% Fe). In studies carried out from 2018 to 2020, Rosahumus was applied to the soil before tuber planting and again just before ridging, using a spray solution of 4.5 kg $ha^{-1}$ dissolved in 300 L $ha^{-1}$ of water [121]. This application resulted in a notable increase in tuber yield compared to the control group that did not use humic preparations. Similar results were observed in a study by Rizk et al. [122], where the addition of humic acid to irrigation water enhanced plant growth parameters and potato tuber yield. Furthermore, research has shown that treatments involving humic acid and algae extracts lead to significant improvements in potato plant morphology and yield. The application of humic acid in combination with Alga 600 and Sea Force 2 resulted in substantially higher values for vegetative features and yield characteristics [123]. These findings underscore the potential of humic preparations and their synergistic effects with algae extracts in enhancing potato productivity and quality. Studies by Man-Hong et al. [124], demonstrated that the application of humic acid led to significant increases in tuber yield, particularly under varying levels of water retention. Specifically, yield improvements ranged from 34.5% to 63.5% under 45% water retention, 35.9% to 37.3% under 60% water retention, and 23.4% to 27.1% under 75% water retention. By contrast, research by Suh et al. [125] did not observe significant differences in tuber number or total yield after spraying potato plants with fulvic acid at different intervals post-tuber planting compared to the control group. However, when humic acid was applied to the soil before planting potato tubers at rates of 40 and 80 g $m^{-2}$, an increase in the weight of large tubers was noted. Furthermore, studies by Ekin et al. [126] demonstrated that treating potato tubers with a combination of humic acid and plant growth-promoting rhizobacteria (PGPR) strains, specifically *Bacillus megaterium* and *Bacillus subtilis*, led to significant improvements in plant

growth, tuber yield, and overall tuber quality. These findings underscore the potential benefits of combining humic acid with microbial inoculants for enhancing potato productivity and quality. Wadas and Dziugieł [127] found that the use of humic and fulvic acids in HumiPlant (leonardite extract), as well as the seaweed extracts Bio algeen S90 (*Ascophyllum nodosum*) and Kelpak SL (*Ecklonia maxima*), had a significant effect on tuber starch content in some potato cultivars but did not affect the content of total sugars (glucose, fructose, and sucrose), monosaccharides (glucose and fructose), or sucrose.

### *6.2. Arbuscular Mycorrhizal Fungi*

The association of arbuscular mycorrhizal fungi (AMF) with most terrestrial plants is geographically ubiquitous and occurs over a broad ecological range. AMFs are particularly important in organic and/or sustainable farming systems that rely on biological processes rather than agrochemicals to control plant diseases [128]. Of particular importance is the bioprotection conferred to plants against many soil-borne pathogens such as species of *Aphanomyces*, *Cylindrocladium*, *Fusarium*, *Macrophomina*, *Phytophthora*, *Pythium*, *Rhizoctonia*, *Sclerotinia*, *Verticillium* and *Thielaviopsis* and various nematodes by AM fungal colonization of the plant root [129]. AMF plays a crucial role as fertility-promoting microorganisms in soils, enhancing soil health and bolstering crop productivity. Specifically, incorporating AMF can yield numerous benefits: (i) expanding the root system's reach by over 100 times; (ii) enhancing the uptake of immobile soil mineral nutrients; (iii) mitigating abiotic stresses such as drought and temperature fluctuations; and (iv) promoting soil aggregation, which is crucial for improving soil structure and preventing erosion [130]. Thus, AMF application emerges as pivotal in organic farming, as it enables plants to thrive through enhanced assimilation of low-concentration mineralized soil nutrients [131]. On potato crops, several scientific studies to assess the impact of AMF on production showed that trial inoculation resulted in higher yields and larger tubers than treatments using conventional chemical fertilizers. Mycorrhizal potato plants were reported to show improved growth and development, pathogen resistance, and productivity compared to non-inoculated potato plants [132]. Furthermore, it is acknowledged that AMF isolates may exhibit host genotype specificity [133]. Douds et al. [134] investigated the impact of inoculating potato plants (*Solanum tuberosum* L. cv. Superior) with arbuscular mycorrhizal (AM) fungi in a field characterized by very high phosphorus availability (375 μg $g^{-1}$ soil) over two growing seasons. The inoculation treatments included a commercially available inoculum containing *Glomus intraradices*, mixed species inocula produced on-farm using compost and vermiculite, and a control treatment of freshly prepared compost and vermiculite mixture. The study compared two farming systems: one using conventional chemical fertilizers and the other using dairy manure composted with leaves to meet recommended nutrient levels. In the first year, AM fungi inoculation significantly boosted tuber yields by 33% under conventional fertilizer application and 45% with compost addition compared to the controls in each system. The second year showed a smaller response, with yields of inoculated plants being 10 to 20% higher than controls. The effectiveness of AM fungi in large-scale potato production was further supported by an analysis of 231 field trials using the same AMF inoculant (*Rhizophagus irregularis* DAOM 197198) over a four-year period in North America and Europe under real-field conditions [135]. In a study by Khosravifar et al. [136], potato plants were inoculated with *Claroidoglomus etunicatum* and *Rhizophagus intraradices*. The presence of *R. intraradices* led to a significant increase in tuber yield (32.5–36.0%) compared to non-inoculated control plants, with a maximum root colonization percentage of 54.2%. Arbuscular mycorrhizal fungi (AMF) have been shown to enhance the drought, salinity, and disease tolerance of potato plants by improving water and nutrient uptake and enhancing overall soil structure [137]. Lombardo et al. [138] explored the impact of mycorrhizal inoculants in combination with either full or reduced fertilizer doses on the yield and physiological characteristics of three early potato cultivars grown organically in highly calcareous and alkaline soils. The study revealed that AMF symbiosis improved potato tolerance to limestone stress compared to non-inoculated plants, as evidenced by

enhanced potential quantum efficiency of photosystem II, better plant gas-exchange parameters, and increased marketable yield, attributed to a higher number of tubers per plant and greater average tuber weight. The effectiveness of AMF was particularly notable when half the usual fertilizer dose was applied in areas where soil conditions were less conducive to potato growth. Furthermore, Lombardo et al. [139] demonstrated that soil mycorrhization can significantly enhance the quality of organically grown early potato tubers, especially in low-fertility soils such as calcareous soils, by improving the plant's uptake of essential minerals. Their research highlighted the role of soil mycorrhization in increasing the accumulation of Na, Cu, Mn, and P in tubers, as well as lowering the Na/K ratio, though these effects varied depending on the cultivar and location. In a farmer's experiment in Iran, Abdulkhadum et al. [140] studied the addition of mycorrhiza (control, and 7.0 g plant$^{-1}$) and three kinds of organic fertilizer: chicken waste (10 t ha$^{-1}$), humic fertilizer (3 t ha$^{-1}$), and vermicompost (4 t ha$^{-1}$). They found that mycorrhiza increased plant height and chlorophyll content; the results of adding organic fertilizer showed that poultry waste significantly improved plant height, leaf area, chlorophyll, number of marketable tubers total yield, dry matter, starch, and N, K in tubers. The mutual interaction therapy (mycorrhiza + organic manure and chicken waste) improved vegetative, quantity, and quality features, plant height, leaf area, chlorophyll percentage of dry matter, the number of marketable tubers, and the total yield.

### *6.3. Biofertilizers*

Apart from Arbuscular mycorrhizal fungi in potatoes, other biofertilizers containing microorganisms that augment the supply of primary nutrients to the main crop have also been applied in organic potato systems [141]. The application of microbiological preparations has been associated with the elimination of putrefactive processes, dissolution of mineral compounds inaccessible to plants, and enhancement of soil fertility and structure, all of which may contribute to increased potato yield. Abou-Hussein et al. [142] demonstrated that a biofertilizer containing *Candida tropicalis*, *Pseudomonas aeruginosa,* and *Bacillus megatherium*, along with the commercial biofertilizer Microbin, increased plant height, leaf number, and both fresh and dry weights of leaves and stems. Additionally, the combination of compost with chicken manure and biofertilizers enhanced dry matter content, specific gravity, and total carbohydrate levels.

A study investigated the effects of combining bio-fertilizers, which included nitrogen fixers (*Azospirillum brasilense* and *Azotobacter chroococcum*), phosphorus-solubilizing bacteria (*Bacillus megaterium* and vesicular-arbuscular mycorrhiza), and potassium-solubilizing bacteria (*Bacillus cereus*), with varying compost rates, compared to the application of mineral fertilizers at 285.6 kg N, 178.5 kg $P_2O_5$, and 357 kg $K_2O$ per hectare, on potato crops [143]. The results showed significant increases in both total and marketable potato yields in plots treated with 50% of the recommended mineral fertilizers combined with 23.8 t ha$^{-1}$ compost, whether or not bio-fertilizers were included. Additionally, plots receiving 35.7 t ha$^{-1}$ of compost alone also demonstrated improved yields compared to the control plots that received full mineral fertilizer doses along with 11.9 t ha$^{-1}$ of compost.

Moreover, El-Sayed et al. [143] suggested the adoption of compost combined with bio-fertilizer as an alternative to conventional production, obtaining a lower content of K and better storability in organic potatoes. Minin et al. [144], studied the effects of the level of mineral nutrition provided by compost (from 0 to 160 kg N ha$^{-1}$) and bio preparations (*Flavobacterin* which has an N fixer attribute, and Vitaplan and Kartofen, which have bio fungicide features). The use of both microbiological preparations and compost gave approximately the same effect and increased yields by 35–37% compared to the control. In their research, Bernard and colleagues [98] investigated three distinct disease-suppressive management practices: (1) a *Brassica napus* (rapeseed) green manure rotation crop, (2) conifer-based compost amendment, and (3) the application of three biological control organisms (*Trichoderma virens*, *Bacillus subtilis*, and *Rhizoctonia solani* hypovirulent isolate Rhs1A1). The study was conducted at sites with both organic and conventional

management histories, focusing on their impact on soilborne diseases and tuber yield. Notably, rapeseed rotation led to a reduction in observed soilborne diseases (including stem canker, black scurf, common scab, and silver scurf) by 10% to 52% in at least one year at both sites. Compost amendment exhibited variable effects on tuber diseases but consistently increased yield at both locations. The biocontrol effects on disease varied; for instance, Rhs1A1 decreased black scurf at the conventional site, while *T. virens* mitigated multiple diseases at the organic site in at least one year. Interestingly, the combination of rapeseed rotation with compost amendment not only reduced disease incidence but also enhanced yield. However, biocontrol additions resulted in only marginal additive effects. AlHadidi et al. [145], in a two-year experiment on potato cultivar "Desiree", investigated the possible role of seven different treatments of microbial inoculates including AMF, PGPR, and *Trichoderma* spp. to improve the potato tubers production and quality under irrigated and non-irrigated conditions. The results indicated that the mycorrhizal colonization intensity and mycorrhizal frequency were increased in non-irrigated treated and the control plants over the two years. Most of the treatments did not show arbuscular abundance in both years, except the mixture of *Rhizophagus irregularis* MucL41833 + *Pseudomonas brassicacearum* (41%), *R. irregularis* MucL41833 + *Paraburkholderia phytofirmans* (24%), and *Trichoderma asperelloides* A (33%). For the tuber yield, the treated plants under irrigated conditions had the highest mean. In the first year, *P. phytofirmans* PSJN had the highest yield under irrigation conditions, while in the second year, *R. irregularis* MucL41833 showed the highest yield in the irrigated conditions as well, followed by the control treatment in both years. Starch content was similar between different treatments in both years, without differences with control plants. In terms of total phosphorus content, the control treatment in the second year had the highest total phosphorus content in the irrigated conditions followed by the mixture treatment of the microbial inoculates treated plants *R. irregularis* MucL41833 and *P. phytofirmans*. In a comprehensive study, various biological amendments were assessed for their impact on potato cultivation in greenhouse and field trials conducted in Maine [146]. The evaluated amendments included commercial biocontrol agents, microbial inoculants, mycorrhizae, and an aerobic compost tea. These amendments were tested both individually and in conjunction with different crop rotations. Notably, the amendments effectively introduced microorganisms into the soil, influencing microbial populations and activity based on the specific organisms added. Over a period of 2 to 24 weeks, significant changes in soil microbial community characteristics were observed. While the effects of the amendments were most pronounced early on (2 weeks post-amendment), the impact of crop treatment became more significant in later assessments (10- and 24-weeks post-amendment). In field trials, the outcomes varied. Some microbial inoculants and biostimulants had no significant impact, whereas the application of arbuscular mycorrhizae led to a reduction in stem canker and black scurf by 17–28%. Additionally, in three different two-year crop rotations (barley/ryegrass, barley/clover, and potato, all followed by potato), biological amendments demonstrated a reduction in soilborne diseases and an improvement in yield in certain rotations, while other rotations showed no significant effects. Soil-applied aerobic compost tea, and its combination with a mixture of beneficial microorganisms, reduced stem canker, black scurf, and common scab on tubers by 18–33% and increased yield by 20–23% in the barley/ryegrass rotation but had no significant impact in the other rotations. The mixture of beneficial microorganisms also reduced disease by 20–32% in the barley/clover rotation only. None of the amendments significantly reduced disease in continuous potato plots. Both crop rotation and amendment treatments significantly affected soil microbial community characteristics, with rotation effects being more dominant. Castillo et al. [147] carried out a field trial to assess the effect of the biofertilizer Twin N (containing bacteria of *Azospirillum* genera in a concentration of $1 \times 10^{11}$ UFC $g^{-1}$) on mycorrhizal fungal parameters. Utilizing the potato variety Desireé, three treatments were evaluated: T0 (control with chemical fertilization at planting, CFS), T1 (CFS + 50 kg N $ha^{-1}$ at ridging), and T2 (CFS + 1 L Twin-N $ha^{-1}$ at flowering). Notably, the Twin-N treatment exhibited the lowest root colonization and a

reduced number of spores in the rhizosphere, yet it resulted in a significant increase in tuber yield. Twin-N appeared to enhance the effectiveness of native mycorrhizal fungi. Although differences were observed in disease incidence (specifically dry rot and craters), incorporating the biofertilizer Twin-N into potato cultivation can be a partial substitute for chemical nitrogen fertilization.

## 7. Conclusions

Nutrition and fertility management are challenging for organic crops with high nutritional demands such as potatoes. In particular, the poor availability of nitrogen for the plants in the products used in organic farming is the main cause of the yield gap between organic and conventional. In organic potato production, maintaining proper soil fertility is paramount, given the efficacy of organic fertilization in organic systems depends on various factors, including the type of fertilizer used (quantity, timing), soil conditions, and weather patterns during the plant's growth stages. Current scientific studies on the use of practices and techniques in organic potato crop production are presented in this review, highlighting the high level of research performed on crop nutrition and soil fertility management. Among organic products, farmyard manure is what has been traditionally used in potato organic systems, but compared to the conventional one, in general, it leads to a marked reduction in yield. Nonetheless, the use of farmyard manure in organic potato cultivation strongly improves soil fertility, making its application a means of supporting long-term environmental preservation. From the numerous studies conducted on potatoes, it has emerged that cover cropping or green manure application can have various beneficial effects on the cropping system such as the increase of soil nutrient content and weed suppression, even if the species used for covering is of great importance; in fact, the best results were obtained with leguminous cover crops, which thanks to biological N fixation ensure that potato yields are not dissimilar to those obtained using mineral fertilizers. Substantial organic potato yields can also be achieved by combining green manure with farmyard manure. Organic amendments such as compost, provide crops with a limited amount of nutrients, primarily nitrogen, necessitating supplementation with organic fertilizers such as leguminous green manure or farmyard manure; in any case, compost does enhance soil fertility. The potential of using biochar to improve macro and micronutrients available for the plant, soil structure, water retention, root growth, and microbial activity also emerged; however, achieving acceptable potato yields is only possible if biochar is combined with other organic products such as bone meal or poultry manure. More recently, biostimulants and biofertilizers (especially arbuscular mycorrhizal fungi) have received increasing attention from the scientific community for their complementary role in potato organic farming. They are useful to enhance soil fertility and, by improving the absorption of water and essential minerals from the soil (above all P), also promote plant growth; in addition, they play a role in the suppression of crop pests and diseases, particularly soil-borne fungal diseases, all of which contribute to increasing organic potato yield. In general, from the literature studied in the review, it also emerged that potato tubers coming from plants fertilized with organic products contain higher sugar and polyphenols content compared to tubers from plants fertilized with mineral fertilizers; some contradictory results are also reported on mineral tuber content, vitamin C, sensory properties.

## 8. Future Research Directions

The application of farmyard manure in organic potato farming greatly improves soil fertility, making it a key practice for long-term environmental sustainability. However, the main challenge in maintaining this practice is the substantial amount of organic manure needed per hectare, which potato growers find difficult to produce. Therefore, emphasizing the development of efficient manure production technologies is advised.

Numerous studies on potatoes have revealed that cover cropping or the use of green manure can significantly benefit the cropping system. Nonetheless, the success of cover cropping largely depends on context-specific management practices, such as the selection of

species, timing of seeding, and termination methods. Unfortunately, many of these factors are not well understood, along with the ecophysiological impacts of cover crops on soil and plant nutrition. It is therefore essential for the scientific community to intensify efforts to address these knowledge gaps. In particular, large-scale, long-term studies employing a multidisciplinary approach are crucial for advancing future research.

A crucial factor in successful organic potato production is the selection of the right genotype. Currently, organic potato farming predominantly relies on varieties developed for conventional agriculture, which are often ill-suited for organic systems, leading to various negative outcomes. It is hoped then that useful studies and research will be carried out to reach the breeding or selection of new varieties characterized by high nutrient uptake efficiency, particularly of nitrogen, while also meeting consumer preferences for quality characteristics.

**Author Contributions:** Conceptualization, A.I.; resources, data curation, writing—original draft preparation, illustrations and tables preparation, A.I. and M.D.; review and editing, A.I.; supervision, A.I. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** No new data were created or analyzed in this study. Data sharing is not applicable to this article.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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