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Abstract: Nanotechnology has become a popular topic in agricultural and animal research, generating significant global interest. Nanoparticles (NPs)-enabled agriculture and animal husbandry (AHs) products have three main principles: crop production, protection, and nutrient enrichment. Research on this topic has grown exponentially in recent years, with an increasing number of peer-reviewed literature and patents on NPs-enabled agriculture and AH products. This study examines and collects data on the various applications of NPs-enabled agricultural products for crop production, protection, and livestock improvement from the core nanotechnological database. The search returned several types of NPs and products used in agriculture and AH, countries that utilize these products at a commercial level, and analysis of these data by phyton, R-statistical software. Our findings show remarkable growth of nanotechnology in agriculture, AH, and research fields for future sustainability goals in the era of climate change.

Keywords: nanotechnology; products ; agriculture; animal husbandry; climate change

1. Introduction

Food security is ensured by agriculture, which also serves as the backbone of growing economies. Climate change, soil pollution from fertilizers and pesticides, and skyrocketing food demands due to a growing global population are a few of the many problems that the agricultural sector is currently encountering [1,2]. The United Nations (UN) has released research estimating that the world's population will reach 8.5 billion in 2030 and about 9 billion in 2050 [3,4]. Therefore, food production must immediately expand by more than 50% to fulfill the demands of the ever-increasing population. However, natural resources like forests, seas, and biological biodiversity, which are vital

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to the survival of the people, are being rapidly depleted as a result of industrialization [5,6]. Consequently, it stresses the importance of bolstering food security and expanding agricultural output. Because it makes farms more resistant to natural stresses that may cause crops to fail, ecological biodiversity is crucial to preserving the environment and ensuring a steady supply of food. The biodiversity that people rely on for their sustenance includes, but is not limited to, crops, animals, forests, and aquaculture systems. There are a lot of plant and animal species that depend on the oceans and woods for survival, providing essential resources like food, fuel, fiber, and fodder. The UN Office for Sustainable Development (UNSSD) blog and other sources all agree that threats to ecological equilibrium have a major impact on food security [7]. Newer methods and approaches are always developing to address these important concerns. The development of consumer products based on nanomaterials (NMs) has the potential to revolutionize contemporary agriculture methods, since this is one step done in this direction [8]. Because of their unique physicochemical characteristics and huge surface area-to-volume ratio, these materials are very reactive and may be easily modified to meet increasing demand [9]. A report from Research & Market institute states that "the Global Nanotechnology Market is poised to grow at a CAGR of around 18.1% over the next decade to reach approximately $173.95 billion by 2025" [10]. An additional analysis by BBC Research asserts that "the global nanotechnology market should reach $ 90.5 billion by 2021 from $39.2 billion in 2016, growing at a five-year compound annual growth rate (CAGR) of 18.2%" [11]. The CAGR is estimated rather precisely for two overlapping periods in the given sources. Figure 1, A is a combined graph of the three market sizes discussed above for 2016, 2021, and 2025. The wide range of sectors that make use of nanoparticles makes market estimation a top priority. According to BBC Research, "the nanomaterials market should reach $ 32.5 billion and $ 77.3 billion in 2016 and 2021, respectively, demonstrating a five-year CAGR of 18.9%" (Figure 1, B) [12–14]. The NMs and nanoscale thin films, among other types of nanomaterials, play a pivotal role in the industry's total growth rate. Agricultural applications of NMs have shown promising outcomes, including enhanced nutritional quality, more efficient growth, and increased output. Agriculture animal husbandry nanotechnological products are a method for enhancing agricultural yields in a variety of climates and improve livestock. NPs are helps in crop production and crop protection. In crop production, crops efficient growth, increased output, and nutritional quality are some of the great agricultural benefits of NPs enabled agriculture products [15,16]. Most people are aware of NAP usage in farming. Agricultural research is one of several practical scientific domains that makes use of nanoemulsions containing NMs of varying sizes [17,18]. However, in NMs based crop protections are new methods of insect pest management in agriculture that can be alternative of traditional method of insect management under agricultural practices [19,20]. Carbon nanotubes, silicon, molybdenum, silver, copper, zinc, manganese, titanium, iron and its oxides, and nanoformulations of common agricultural inputs like phosphate, urea, sulfur, validamycin, tebuconazole, and azadiractin all are transformed into nanopesticides and nanofertilizers that utilized for crop production and protection for sustainable agriculture in climate change era (Figure 1C). NPs technology, made possible by recent advances in materials science and chemistry, has far-reaching consequences for farming [21–25]. Improving economic growth and addressing the nutritional needs of people in all countries are both aided by agriculture. Weeds, economic position, population, bug and pest populations, and other variables all have an impact on sustainable agriculture. In order to face the problems and demands, it is crucial to improve the agricultural aspect's grade [26]. Fertilizers and insecticides both need substantial amounts of chemicals (30–40%) to obtain the desired crop output. The soil may not benefit from potassium, nitrogen, and phosphorus in the long term due to their low efficiency rates of 20-40%. This unfertilized soil surrounding plateau regions affects the total output of food crops [27]. The farmers are confronted with several challenges, such as compound impacts, economic crisis, adverse climate change effects, and low yield. It is more important than ever to manage a multitude of risks in the agriculture economy due to the challenges brought about by a growing global population, shifting dietary preferences with an increased demand for meals derived from animals, and climate change [28]. To tackle these challenges, a lot of new technology needs to be chosen to increase farmer standards and agricultural yields. Using nanosensors grounded on the nanotechnology integrated

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into all agricultural concepts is at the core of this technology. With the help of nanotechnology, farmers can combat the overabundance of greenhouse gases—methanol, carbon dioxide, and nitrogen oxide—caused by shifting weather patterns and rising global temperatures, all of which have a significant impact on harvest success. Atrazine herbicide nanocarrier capsules and other growth regulators, as well as staple crop growth, food manufacturing, nutritional value, and controlled herbicide release efficiency, are all enhanced by this [29]. Some of the materials used to increase crop output include aluminum (Al), zinc oxide (ZnO), silicon (Si), titanium dioxide (TiO_2), copper (Cu), and aluminum oxides (Al_2O_3). Plants are protected by these NPs, and food sustainability is improved; for example, Ag NPs have a higher nutritional value in the yield and a greater impact on yield quality than antibacterial properties (Figure 1 C) [30]. We conducted a thorough analysis of the widespread use of nano-enabled products in crop production, crop protection, and animal husbandry.

These NPs include fertilizers, algicides, fungicides, disinfectants, and pesticides, among others. Additionally, they are used as veterinary disinfectants, wound drugs, aquaculture supplements, antibiotics, and disinfectants for livestock. Our meta-analysis aimed to answer the following questions: 1) How many nano-enabled products are currently being used in crop production, crop protection, and animal husbandry? 2) How many NPs are present in these products? 3) How many nations are currently utilizing these nano-enabled products worldwide? Our study aims to provide a comprehensive understanding of the commercially available and sustainable use of nano-enabled products in agriculture and animal husbandry.

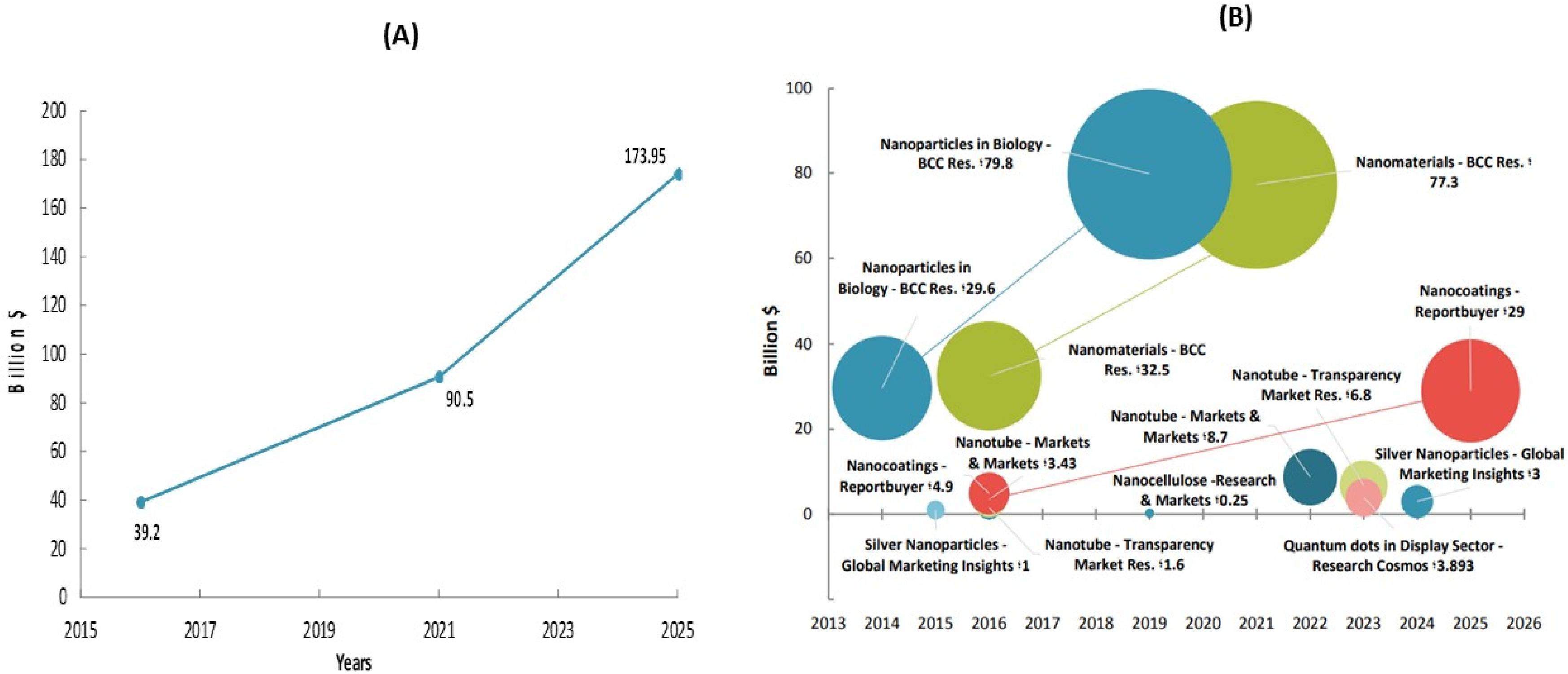

Figure 1. (A) market value of nanotechnology-based (B) products are increased each year [31].

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Figure 1C. Different nano-enabled products that commercially utilized for crop production protection and AHs.

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2. Materials and Methods

To explore the current research progress and commercial utilization of nano-enabled products and their effects on crop production protection, animal husbandry followed by meta-analysis was conducted to identify and collect relevant data [32]. By utilizing three most popular databased like Nanotechnology Products Database (NPD) (https://product.statnano.com), The Nanodatabase (https://nanodb.dk/) and Nanowerk (https://www.nanowerk.com) provides a reliable source of information about nanotechnology products, currently used in a broad range of industrial, agriculture and AHs applications. Above mentioned databases are important sources of information that cover various aspects of consumer products enhanced by nanotechnology. This online resource databased provides users with a comprehensive inventory of consumer product information, making it easier for them to access valuable data and analysis. This resource plays a crucial role in promoting the use of nanotechnology in commercial products, thereby encouraging innovation and technological progress. One of the most significant aspects of these databases are their commitment to open access. This means that stakeholders can easily access important insights and statistics related to nanoproducts available in markets around the world. These resources serve as gateways to the latest statistics and trends, providing stakeholders with the knowledge they need to make informed decisions in a rapidly evolving landscape of nanotechnology applications. The primary goal of these databases is to gather, analyze, and share information about products enhanced by cutting-edge nanotechnology. The verification process adheres to internationally recognized standards, particularly those defined by ISO/TS 80004-1:2015 and ISO/TS 18110:2015. These standards provide clear definitions of nanotechnology and nano-enabled products, ensuring consistency and accuracy in the classification and evaluation of recorded products within the databases. The data available within these repositories encompasses a wide range of information that is critical for stakeholders. This includes details on brands available in markets, product features that are enhanced by nanotechnology, specifications of nanomaterials used in products, as well as certificates and approvals obtained by manufacturers or products. Such comprehensive data sets empower researchers, manufacturers, regulators, and consumers alike, facilitating informed decision-making and fostering the responsible advancement of nanotechnology applications in consumer products. We collected and analysis the information of agriculture and AHs related nano-enabled products statistical data and results were processed and visualized using R and Python programming [33,34].

3. Results and Discussion

3.1. NPs in Agriculture and Animal Husbandry Products

According to the evaluation of the nano-database, there are over 259 nano-enabled products available for commercial use in the field of agriculture and AHs (animal husbandry) (Figure 2). Out of these, 46.33% are fertilizers, 18.53% are plant protection products, 10.42% are related to plant breeding, 3.09% are for soil improvement, and 21.62% are for AHs (Figure 2). These nano-enabled products can be commercially utilized in agriculture and AHs. Figure 2 information is related to different categories of agricultural practices such as Animal Husbandry, Fertilizers, Plant Breeding, Plant Protection, and Soil Improvement. There are a total of 56 products in Animal Husbandry, 120 in Fertilizers, 27 in Plant Breeding, 48 in Plant Protection, and 8 in Soil Improvement. The distribution of companies operating in these categories is 25 for Animal Husbandry, 52 for Fertilizers, 8 for Plant Breeding, 24 for Plant Protection, and 3 for Soil Improvement. When it comes to countries, 14 are involved in Animal Husbandry, 19 in Fertilizers, 7 in plant breeding, 12 in plant protection, and 3 in soil improvement (Figure 2). This data provides an overview of the global agricultural landscape, highlighting the abundance and distribution of products, companies, and participating nations in these critical sectors.

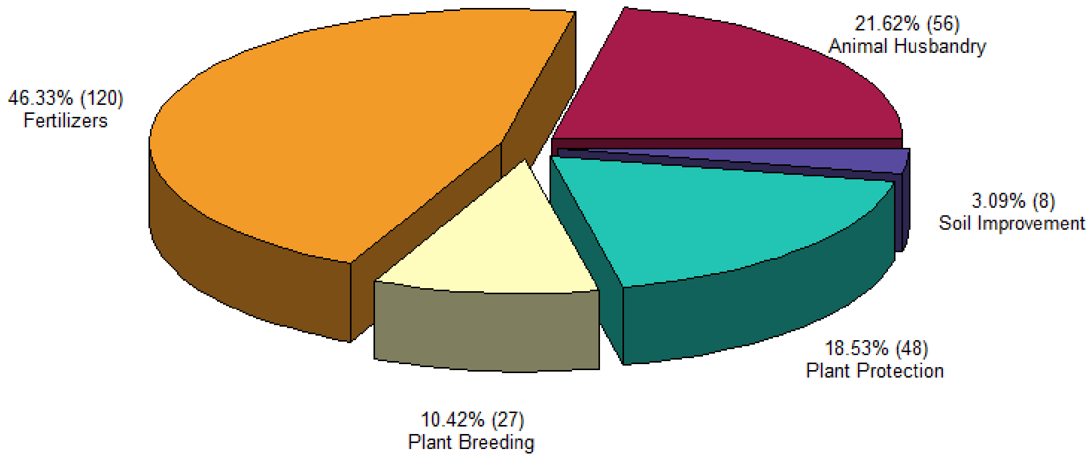

Figure 2. Type and number of different NPs-enabled products available commercially.

The agricultural industry has a range of products that serve different purposes in animal husbandry and plant growth (Figure 3). Fertilizers offer over 100 products, ranging from traditional fertilizers to controlled-release nanocomposites and fertilizer boosters (Figure 3A). Chelates and fertilizer chemicals are examples of the nuanced aspects of fertilizer formulation (Figure 3A) [35]. Nano-enables plant breeding products, such as plant growth regulators, hormones, and fruit enhancers, optimize plant development and influence traits such as growth patterns and fruit quality (Figure 3C) [36–41]. Horticultural Domes and reflectors create controlled environments for optimal plant growth. Plant protection products, including pesticides, fungicides, algicides, and herbicides, cater to the diverse needs of safeguarding crops against various threats (Figure 3B) [42]. Agricultural films and biocides offer additional dimensions to crop protection strategies [43,44]. Soil improvement nano-enabled products such as soil enhancers and agricultural films contribute to maintaining soil fertility, structure, and overall quality [45,46]. Fungicides and insecticides are included to highlight the integrated approach to agriculture, addressing both plant health and the surrounding environment. Aquaculture supplements and veterinary disinfectants are two of the most popular categories, with 13 and 9 products respectively (Figure 3D). Livestock supplements, antibiotics, and wound drugs, as well as poultry enzymes, supplements, and cow nutrients, provide a diverse range of specialized items (Figure 3D). The broad range of nano-enable products across these categories demonstrates the dynamic and evolving nature of agricultural technology aimed at fostering sustainable and efficient farming practices [47].

3.2. Type of NPs Utilized in Agriculture and AHs Products

3.2.1. Crop Production

Nanotechnology has a significant role in crop production by incorporating various NPs into agricultural fertilizers and plant breeding products. The Figure 3A provides an overview of the types of NPs used in fertilizer products, such as controlled-release nanocomposites, chelates, and fertilizer chemicals. Notable examples of NPs utilized in these formulations include potassium, zinc, calcium, and other elements in varying quantities. These NPs help enhance nutrient delivery and improve the efficiency of fertilizers in promoting plant growth [25,48]. In addition, specific NPs like Ag, ZnO, Fe, Boron (B), and others find applications in plant breeding products, particularly in the development of plant growth regulators (Figure 4) [49]. The integration of nanotechnology in crop production reflects ongoing efforts to optimize nutrient utilization, improve soil health, and promote sustainable agricultural practices by utilizing the unique properties of NPs.

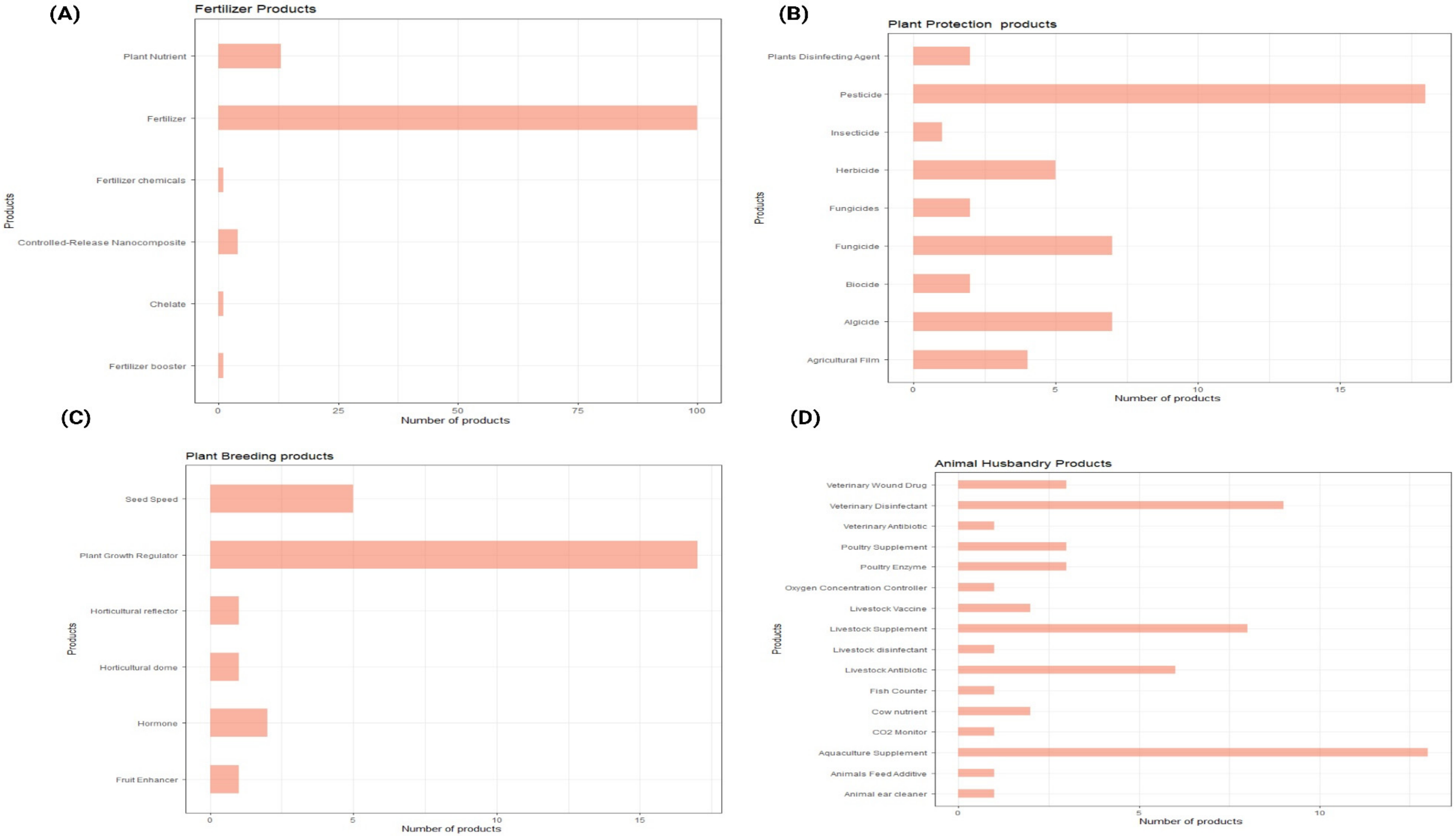

Figure 3. Currently commercially available, utilized nano-enabled products in crop production and protection (3 A-C). Also, AHs related nano-enabled products.

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In the field of agricultural fertilizer products, the incorporation of NPs is crucial in enhancing their effectiveness. Potassium (K), an essential nutrient for plant growth and K-NPs appears in three fertilizers products and shows versatility with two instances in controlled-release nanocomposites-based products (Figure 5). However, it is noticeably absent in chelates or chemicals fertilizer. Zn, another vital element and four Zn-NPs based fertilizers commercially available (Figure 5). Although Zn-NPs is not present in controlled-release nanocomposites, zinc has a unique application in chelates, emphasizing its diverse uses.

Various scientific research also support this statements e.g., Azam et al. (2022) conducted an experiment with ZnO NFs for soil and foliar application. They used six treatments, including control, salt, and four concentrations of nanofertilizer (40, 80, 120, and 160 mg/kg). The results showed that compared to the control plants, the treated plants had 61.1% more growth, 51.8% more photosynthetic pigments, and 49.25% more antioxidant activity. In a foliar spray study with five treatments (control, 10, 20, 30, and 40 ppm nanofertilizer concentrations), plant growth was raised by 59.28%, photosynthetic pigments by 48.19%, and antioxidant activity by 52.91%. The results showed that using ZnO as a NFs improved the growth and extract yield of a maize cultivar. This suggests that ZnO might be used to improve the quantitative and qualitative value of crops grown on soils that are insufficient in Zn. Four year experiment show that application of zinc complexed chitosan nanoparticles (Zn-CNP) on wheat increased the yield with nonfortified means increased the Zn content in two durum wheat genotypes (MACS 3125, an indigenous high yielding genotype and UC 1114) [51]. Different concentration of ZnO NFs were used in coffee (*Coffea arabica* L.) [52], pepper plants (*Capsicum chinense* Jacq.) [53], sunflower (*Helianthus annuus* L.) [54], pomegranate (*Punica granatum* cv. *Ardestani*) [55], Millet (*Setaria italica* L.) [15], turmeric (*Curcuma longa* L.) [56], Mountain pepper (*Litsea cubeba* (Lour.) Persoon) [57], dragonhead (*Dracocephalum moldavica* L.) [58], squash (*Cucurbita pepo* L.) [59], lettuce (*Cucumis sativus* L.) [60], soybean (*Glycine max cv. Kowsar*) [61] that increased yield and nutrition's of all these crops.

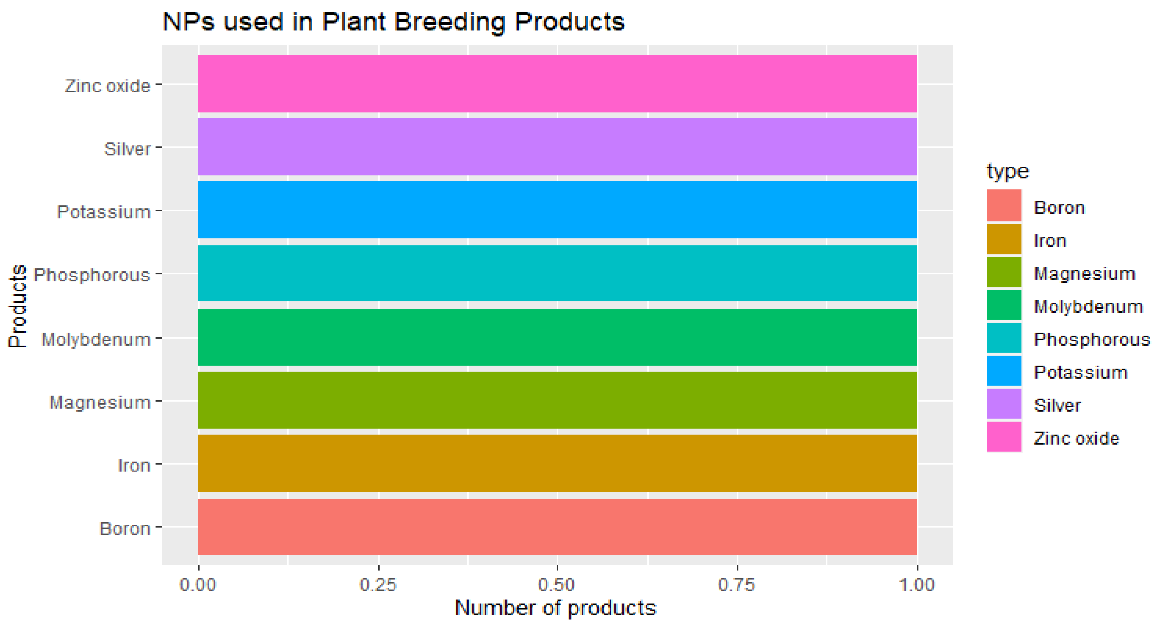

Figure 4. Different NPs based plant breeding products and enhanced the plant growth and development.

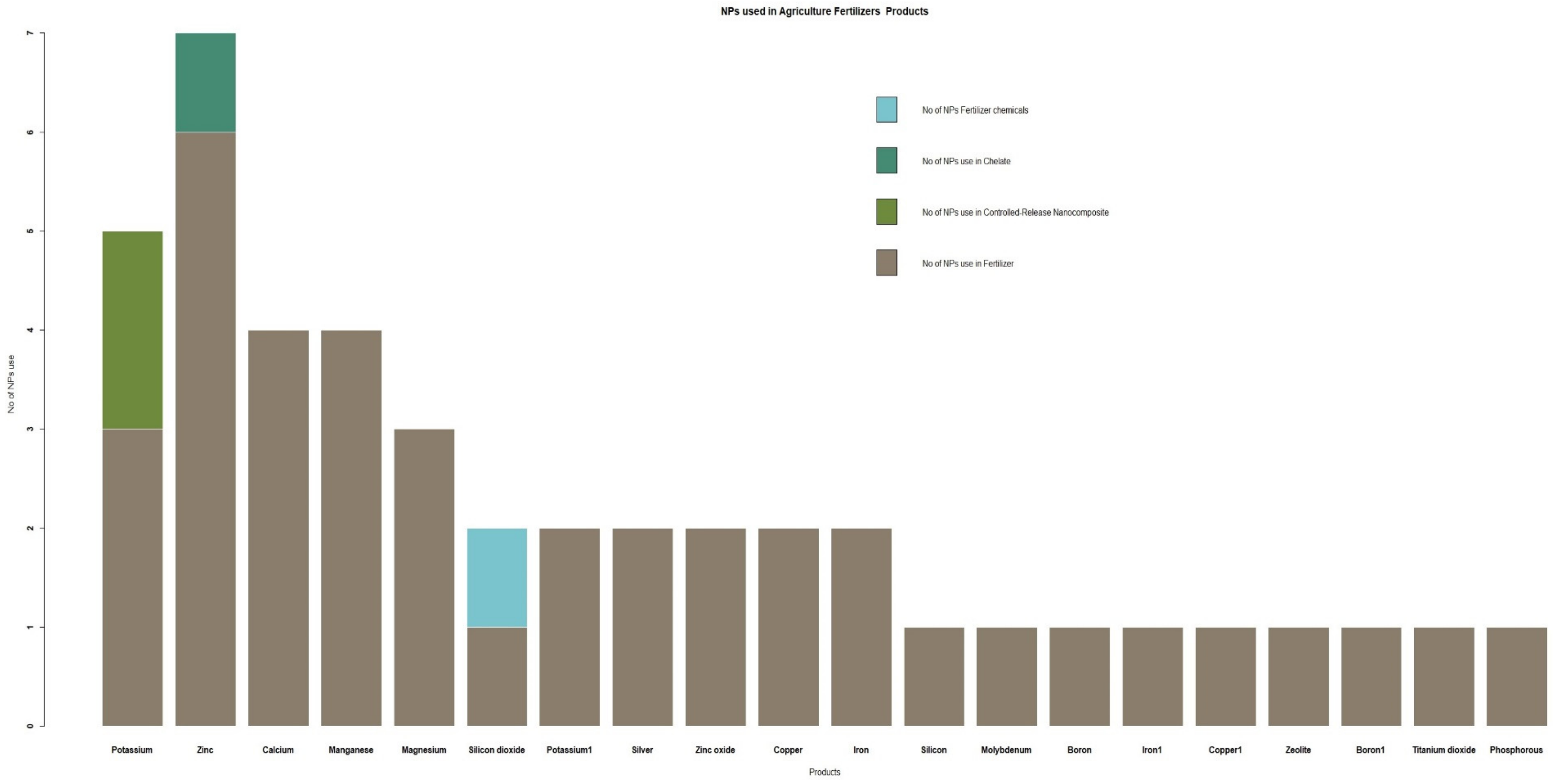

Figure 5. Application of different NPs as ingredients of chemical fertilizers or directly utilized as nanofertilizers, chelate and nanocomposite that help in crop production.

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Calcium NPs based 4 nano-enabled products are used for commercial purpose but these NPs not widely used as controlled-release nanocomposites, chelates, or fertilizer chemicals (Figure 5). To address these issues, one effective solution is to use calcium fertilizer [62]. Calcium is referred to as "lazy Ca" due to its passive characteristics. The root system can absorb fertilizer from the soil and transport it to the fruit, but this process is too slow to meet the fruit's calcium needs as they develop and grow. The use of foliar sprays accelerates the absorption of calcium by the fruit and crops [63]. Agricultural output has progressively benefited from this type of fertilization due to its rapid nutrient absorption, positive fertilizer impact, high relevance, and convenient application [64]. When calcium cations and phosphate anions are present in a supersaturated solution, the first phase that precipitates out is known as amorphous calcium phosphate, or ACP. In X-ray diffraction tests, the compound looks amorphous, while having an apatitic short-range structure [65]. This is due to its extremely tiny crystal size. Nanoparticles of ACP (nACP) have recently been the subject of research into their fertilizing potential, with promising outcomes. These compounds may adsorb tiny molecules (like urea) on their surface and are more reactive and soluble than hydroxyapatite, allowing them to carry more macronutrients in their payloads. Despite the small sample size, the most important finding is that the NUE improved while using nACP, which is a testament to its potential features. The growth chamber was used for the pot trial with U-nACP as the control, with no fertilizer applied; with U-ACP, 15 kg N ha^{-1} sprayed suspension + 60 kg N ha^{-1} granular DAP; and with 150 kg N ha–1 granular DAP [66]. Plants grown in a 1:1 clay-loam soil/sand combination under a 12-hour light/dark cycle outperformed those grown in a positive control group on all measures of crop output and grain quality.

In a separate study, U-nAC was used in several treatment combinations—control (N-starvation), U-nACP (1 mM U), U-nACP 0.5 (0.5 mM U), and Urea (1 mM)—in a hydroponic environment. Similar root and shoot biomass was achieved with U-ACP with a 50% lower N content after 7 days of N-starvation followed by treatments in *Cucumis sativus*, as compared to conventional U [67]. Research on *Vitis vinifera cv.* shows similar results. The control group included Tempranillo, whereas the experimental groups included Vitis vinifera cv., Urea solutions of 3 kg N ha^{-1} and 6 kg N ha^{-1}, as well as a suspension of U-nACP at 0.4 kg N ha^{-1} [68]. Applying U-nACP in an outdoor pot experiment with sand, peat, and clay (50–35–15% by volume) yielded quanti-qualitative metrics that were on par with plants handled using more traditional methods in *Vitis vinifera cv. Pinot Gris* [69]. The same applies to manganese (Mn^{2+}) and magnesium (Mg^{2+}) NPs, both of are featured in three fertilizers mean three types of Mn^{2+} and Mg^{2+} NPs based fertilizers are commercially available but absent in the other categories (Figure 5). Plants rely on Mn^{2+}, a key micronutrient, for a variety of functions, including photosynthesis and the production of enzymes. An essential antioxidant structure, manganese is a component of superoxide dismutase, which defends plant cells from free radicals that might damage plant tissue. The water-splitting protein Photosystem II contains manganese, which is an essential element for photosynthesis. The chlorophyll reaction centers also rely on it for electron storage and delivery [70]. One form of Mn^{2+} that plants may absorb is the divalent ion Mn^{2+}. Uptake of manganese is frequently less than 1 kg Mn/ha in cereals and around 2 kg Mn/ha in sugar beetroot, and only in very tiny amounts [71]. Increased photosynthetic efficiency leads to higher crop yields and better quality [72]. This is because Mn^{2+} fertilizer improves plant nutrition. Overall, calcareous soils, soils with high pH (arid and semi-arid parts of the world), and particularly soils with poor aeration are the most common places where manganese deficiency is found, but it is distributed widely geographically. The erosion of the soil's surface is also caused by a manganese shortage. In most cases, organic matter in the soil affects the concentration of dissolved manganese. As a result of severe leaching, manganese is intrinsically low in certain podzolic soils. Since the solubility of manganese is lowered one hundred times for every one unit of pH, the solubility of manganese will decrease as the pH increases. Mn^{2+} shortage severely damages the structure of chloroplasts since they are the most sensitive components of cells under these conditions. When Mn^{2+} deficit occurs, net photosynthesis and chlorophyll levels drop [73]. Over all utilization of Mn NPs based fertilizers can resolved this problem and may increase the crop production. Common bean yield, flowering number, and vegetative growth are all improved by application of fertilizer containing 40 mg/L of Mn NPs

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[74]. Nano-fertilizers made of manganese oxide (MnO_2-NPs) were manufactured for use as a foliar application. Over the course of two growing seasons in 2020 and 2021, researchers planted common dry beans in clay soil and measured the impact of various concentrations of MnO_2-NPs on plant parameters, yield, chemical quality of leaves and seeds, genomic DNA, and several genes encoding proteins. Over the course of two growing seasons, the results demonstrated that a common dry bean's growth criteria were improved by 45.2% and its yield percentage by 48.9% when treated with MnO_2-NPs at a concentration of 30 ppm. In reaction to MnO_2-NPs, the chemical quality of seeds and leaves altered. Additionally, MnO_2-NPs at concentrations of 30 and 40 ppm had a more substantial impact on the genomic DNA and some genes that encode proteins of the plants compared to other concentrations [75]. Several biological systems rely on Mg^{2+} for various physiological processes [76,77]. Several variables, particularly soil acidity, greatly affect its availability [78]. However, Mg^{2+}shortage stunts plant development and growth, leading to poor quality and low yields in the future [79,80]. Consequently, a variety of fast-release Mg (F-Mg) fertilizers are used to boost crop yields. In general, F-Mg fertilizers incorporate magnesium sulphate heptahydrate, magnesium chloride hexahydrate, and magnesium nitrate hexahydrate [81]. Unfortunately, magnesium is one of the most easily leached cations due to its high hydrated radius and lowest ionic radius [82]. Soil magnesium is also lost due to severe leaching caused by rain and high temperatures [83]. There is a loss of resources due to the easy leaching and low utilization rates of these Mg fertilizers [76,84]. Therefore, to address the drawbacks of F-Mg fertilizer, a slow-release Mg (S-Mg) fertilizer must be developed. SiO_2, an emerging player in agricultural technology, is present once in fertilizers and additionally in fertilizer chemicals, indicating a dual role (Figure 5). Other noteworthy NMs such as Ag, ZnO, Cu, and Fe each have two instances in fertilizers, emphasizing their substantial contributions. Mn, Si, Mo, boron, zeolite, TiO_2 and phosphorus each make a singular appearance in fertilizers (Figure 3). All these micronutrients based NFs can plays important role in growth and development of crops e.g *Punica gratatum cv. Ardestani* [85], Maize (*Zea mays* L.) [86], pearl millet (*Pennisetum Americanum* L.) [87,88], mustard (*Brassica napus* L.) [89], spinach [90], watermelon [91], lettuce [92], Lemna minor, and wheat [93]. Shifting to the realm of plant breeding products, the focus is on specific NPs and their association with plant growth regulators. Silver, zinc oxide, iron, boron, potassium, phosphorus, magnesium, and molybdenum, each featured once, showcase their potential in influencing plant growth and development (Figure 5). This intricate interplay between NPs and plant growth regulators underscores the sophisticated strategies employed in modern agricultural practices to optimize crop yield and quality [60,94–97].

3.2.2. Crop Protection

Nanotechnology is being used in crop protection through the incorporation of NPs in plant protection products such as algicides, fungicides, plants disinfecting agents, and pesticides. An increasing number of novel antibacterial chemicals are being developed using nanotechnology to combat against harmful bacteria, fungus and algae that may affected the crop protection and production [98]. The use of nano-scale biocidal chemicals in modern agriculture is crucial due to their higher efficiency against infections [99,100]. Extensive study has been conducted on the properties of metal NPs in relation to their antibacterial action (Figure 6). Ag, Al, Se, CuO, MgO, SiO_2, TiO_2, and ZnO are among the NPs that have broad range of antimicrobial effect against various microorganisms [45,101–103]. A researcher states that five main theories have been put forward to explain how metal NPs are antibacterial [104]; first nutrient absorption systems and membrane transporter damage second DNA is one of several cellular organelles damaged by ROS generation, which causes cellular and oxidative stress. Third protein activity and permeability are altered by the release of toxic ions. Fourth the interaction between DNA and the hazardous ions released by NPs leads to cell death and genotoxicity. Metabolic process interference affects energy generation, membrane oxidation, and protein oxidation. Fifth the biocidal characteristics of nanoparticles are designed to give unique and improved antibiotic action, depending on their size and dose [105]. There are two main types of nanopesticides, distinguished by the mode of active ingredient administration. Type-I nanopesticides include nanoparticles made of metals that serve as active ingredients, whereas type-II nanopesticides

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use nanocarriers, including polymers, lipid droplets, or clays, to contain the active components [106]. The Figure 6 shows the types and quantities of NPs used for these purposes. Ag NPs are prominently used in various categories, with six algicides and one in fungicides nano-enabled products (Figure 6). Some recent research finding also provided a commercial value of these Ag NPs antimicrobial products like *Ocimum basilicum* (basil) [107], *Ananas comosus* (pineapple) [108], *Andrographis paniculate* [109,110], *Vitex negundo* [111], and *Cinnamomum camphora* [112] are some of the important plants whose extracted phytochemicals act as chelating agents during the green synthesis of Ag-NPs show a potential antimicrobial activities. Over a 7-day treatment period, an biogenic Ag-NPs synthesized from *Euphorbia prostrates swallow* grass leaves demonstrated to achieved approx 100% of mortality of *S. oryzae* [112]. Similarly effective is observed against the polyphagous pest *Spodoptera litura* by Ag-NPs which synthesized from pomegranate extract [113]. At a dosage of 25 mg/L, the extract of *Cissus quadrangularis* mediated by Ag-NPs had a significant mortality impact on the adult flies, *Hippobosca maculate* [114]. The polyphagous pest Tetranychus urticae may be effectively killed and its eggs prevented from hatching when AgNPs are synthesised using Saponaria officinalis root extract [115,116]. Cu NPs are also used, with two nano-enabled products as plants disinfecting agents and one in fungicides (Figure 6). Biogenic synthesis of Cu NPs using *Punica granatum* peels show positive effect against green peach Aphid [117]. Also Cu NPs also show as fungicides against *Fusarium kuroshium* [118], *Fusarium wilt* [119], *Fusarium* [120], *Fusarium solani, Neofusicoccum sp. Fusarium oxysporum* [121] , *Alternaria brassicae* [122]. Micelles, which represent a unique type of NP, are used in pesticides [123]. The integration of these NPs in plant protection products highlights their potential to improve the effectiveness of pest and disease management strategies in agriculture.

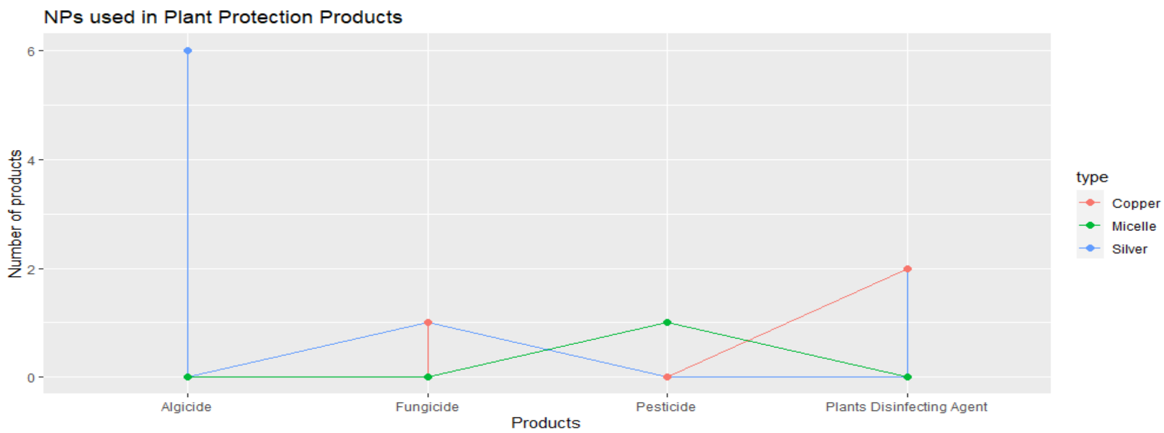

Figure 6. Application of Cu, Ag and micelle NPs for crop protection. These innovative approaches contribute to sustainable farming practices by providing targeted and efficient solutions for crop protection while minimizing environmental impact.

3.2.2. AHs

The fields of veterinary medicine, animal health, and animal production might all benefit from nanotechnology [124]. NPs derived from a variety of metals and elements have found utility in a wide range of agricultural and environmental contexts. Ag NPs stand out among these nanoparticles because of their impressive antibacterial properties, which they employ to kill and suppress pathogenic organisms of bacterial, fungal, and viral origin. In animal husbandry, Ag NPs is a widely used active ingredient in a variety of products that aim to promote animal health and hygiene. It is a versatile component that is commonly found in different categories of animal husbandry nano-enabled products. Ag NPs is particularly effective in fighting against animal pathogens and as Figure 7 show that three Ag NPs enabled veterinary disinfectant products are commercially available. It is also an essential ingredient used as veterinary wound drugs and, in our finding, show that within two nano-enabled products with Ag NPs utilized which have significance importance to preventing infections and promoting wound healing in animals (Figure 7). In addition, Ag NPs based one more product is included which act algicides veterinary antibiotics to combat infections (Figure 7). It is also

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present in one more single product as livestock supplements and disinfectants with a importance role in improving livestock nutrition and maintaining hygiene in animal facilities (Figure 7). In previous research also show that Ag NPs have potential effect to manage most probably all live stock related problem. Evidence from studies by Tomar and Preet [125] and Avinash et al. [126] suggests that neem-mediated nanoparticles are superior to albendazole or neem alone in combating helminths. Avinash et al. (2017a) found that neem-mediated Ag NPs had IC50 and IC90 values that were 99.5% and 97.2% lower, respectively, than albendazole. That means albendazole is not as deadly as neem-mediated Ag NPs. According to Tomar and Preet [125], another study found that adult *H. contortus* motility was reduced by 15% to 85% when exposed to 1-25 μg/mL of neem-mediated Ag-NPs, while the same effect needed 200-1200 μg/mL of neem. The IC50 for adult mortality was 7.89 μg/mL.

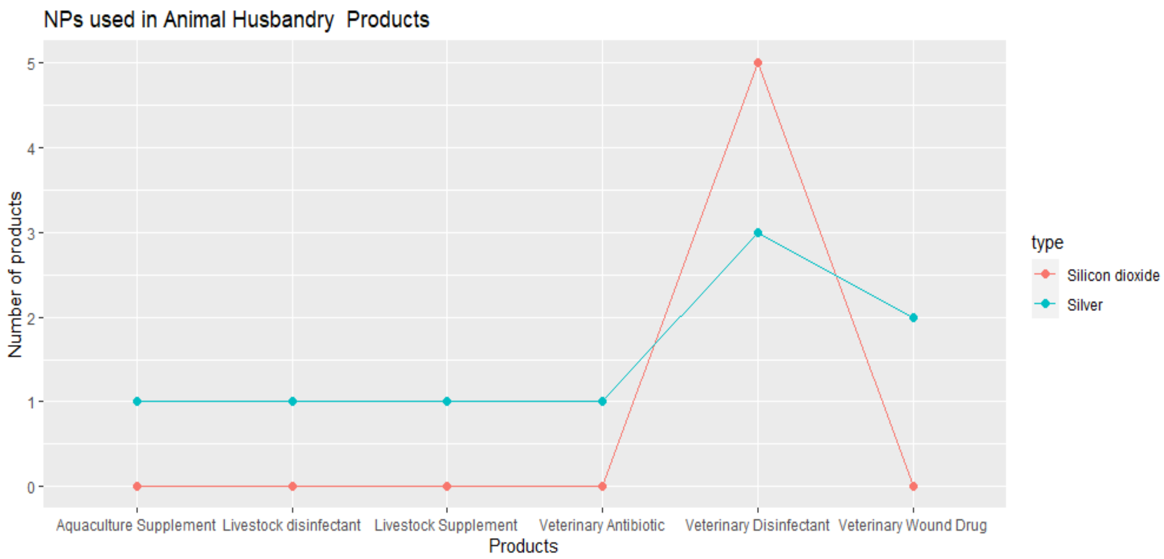

Figure 7. NPs-enabled products utilized in different purpose in AHs.

Another work conducted by Preet and Tomar [125] found that the LC50 of biofabricated Ag NPs from Ziziphus jujuba leaf extract was 98.37% lower than that of the raw leaf extract. Scientists found that the nanoparticle changed the shape of the egg and reduced the amount of nutrients (glycogen, fat, and protein) in adult worms by 5.69–21.81 percent. All these finding suggested that Ag NPs utilized as multiple work veterinary disinfectant, veterinary wound drug, aquaculture supplement, veterinary antibiotic, livestock supplement, livestock disinfectant. In aquaculture supplements, Ag NPs has a one product which play a role in supporting aquatic animal health and growth (Figure 7). Aquaculture, including both freshwater and marine varieties, accounts for a bigger portion of the livestock-based trade business, which has seen major developments in nanotechnology. Sustainable practices incorporate nanotechnological applications because they allow for the effective and customized dose of essential oils and proteins, which improves the marketability of these products in terms of quality and consumable characteristics. Significant runoff avoidance has resulted from agricultural techniques that are in line with mixed farming integrated with fish culture, contemporaneous water conservation, and ground water replenishment (Poddar et al., 2018). Coordination of these activities, promotion of health and nutrition to prevent pathological abnormalities, and accurate tracking of growth parameters are all made possible with the use of smart nanosensors and nano medication delivery vehicles. Applications based on nanoentities extend beyond fish to include other aquatic microbial flora and fauna, such as certain types of algae, plankton, etc., which may be equally profitable as fish or seafood in terms of economic value. However, practical applications of lanthanum-based NPs have been reported, according to Diaz et al. [127], to be able to remove phosphate compounds and other impurities from water, thereby avoiding algal blooms. Included in sustainable agricultural techniques, this procedure can help with eutrophication cures [128]. This means that groundwater levels would not be fouled or cross-

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contaminated in the long term. The consistent use of silver across a range of animal husbandry products underscores its significance in promoting animal health, hygiene, and overall well-being within the husbandry sector.

3.3 Global Use of NPs-Enabled Products by Countries

Various countries across the globe are involved in the production of industrial products that utilize nanotechnology. The number of such products varies in different categories. In India, the nano-industry is diverse and it produces 50 nano-products in fertilizers, 6 in animal husbandry, 8 in plant protection, 10 in plant breeding, and 1 in soil improvement (Figure 8). Germany is actively engaged in producing 8 nano-products in fertilizers, 22 in plant protection, and 2 in plant breeding categories (Figure 8). The USA contributes significantly with 10 nano-products in fertilizers, 11 in animal husbandry, and 4 in plant protection. The UK showcases its commitment with 8 nano-products in fertilizers, 10 in plant breeding, and 6 in soil improvement (Figure 8). Vietnam focuses on animal husbandry, producing 14 nano-products, and has 1 nano-product in plant protection. Taiwan contributes 6 nano-products in fertilizers, 5 in animal husbandry, and 1 in plant protection. Malaysia specializes in fertilizers, producing 8 nano-products, and has 1 nano-product in animal husbandry. Brazil actively engages in the production of 7 nano-products in fertilizers and 1 in plant breeding. The Netherlands contributes 2 nano-products in fertilizers and 6 in animal husbandry. China is involved in the production of 1 nano-product in fertilizers, 4 in plant protection, and 1 in plant breeding (Figure 8). These nano-enabled products numbers highlight the global commitment to utilizing nanotechnology for various agriculture applications, reflecting efforts to enhance efficiency, sustainability, and innovation in farming practices worldwide.

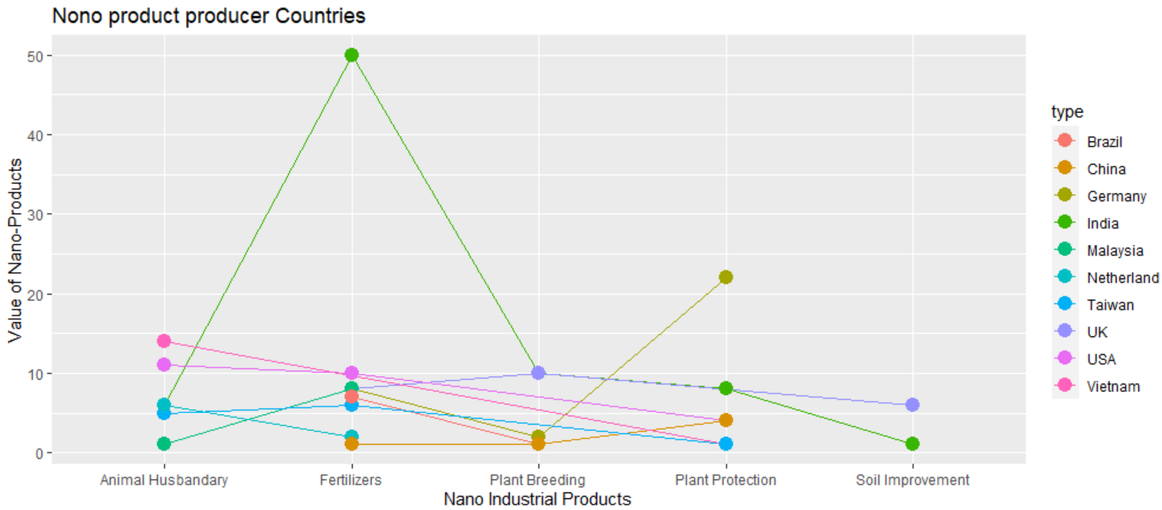

Figure 8. Utilization of NPs-enabled products in different-different countries.

3.4. Global Diversity in the Utilization of Nanoproducts

Various countries incorporate different quantities of NPs into their products, showcasing a diverse range of elements utilized in nanotechnological applications. In India, boron is employed in 2 products, while silver is used in 8, potassium in 2, zinc in 3, magnesium in 2, and manganese in 1 (Figure 9). Germany predominantly utilizes silver nanoparticles in 6 products. In the USA, zinc is found in 1 product, and silver is used in 2. Taiwan incorporates silicon dioxide in 5 products. Brazil employs zinc in 1, calcium in 2, magnesium in 1, and manganese in 1 product (Figure 9). The UK utilizes potassium in 1, zinc in 1, and calcium in 1 product. The UAE incorporates zinc in 1 and manganese in 1 product. Malaysia predominantly uses potassium in 2 products. The Czech Republic engages silver nanoparticles in 2 products (Figure 9). Finally, the Netherlands employs silver nanoparticles in 1 product. These examples underscore the global diversity in nanoparticle utilization, with each country India, Germany, USA, UK, Vietnam, Taiwan, Malaysia, Brazil,

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Netherland, China demonstrating specific preferences for elements in their respective nanotechnological applications (Figure 10).

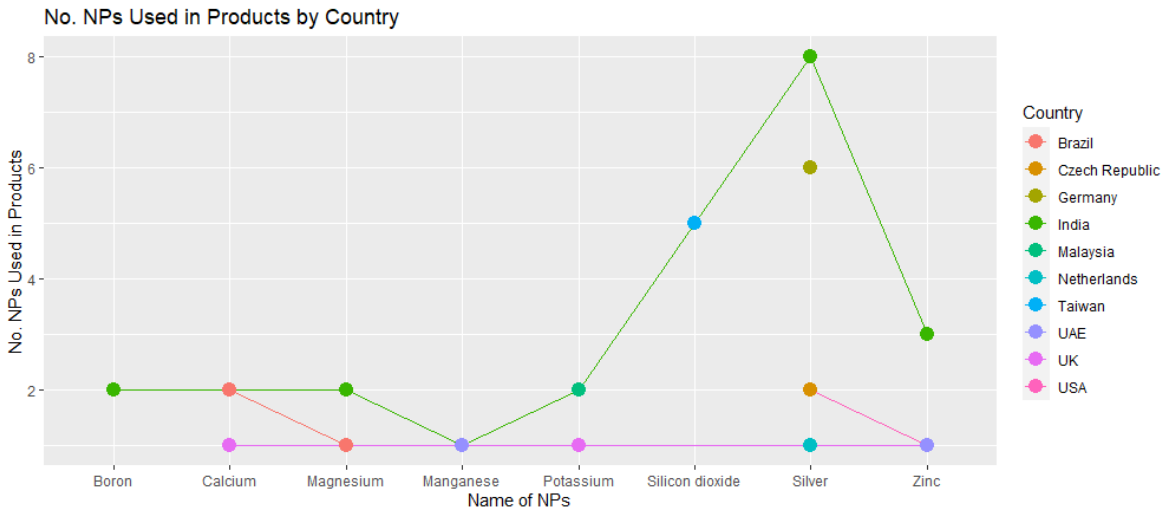

Figure 9. Various countries worldwide use different types of nanoparticles in their products.

Figure 10. Globally, different nations are involved in the application of nano-enabled products in the fields of agriculture and AHs.

4. Conclusion and Future Prospective

Our study has revealed that NPs are being increasingly utilized in agriculture and animal husbandry. They are proving to be effective in crop production, crop protection, and animal health. Our key findings are as follows: 1) Different types of Oxide and Carbon-based NPs can be used in nanofertilizers, chelates, and nanocomposites for crop production; 2) Cu, Ag, and micelle NPs are used for crop protection; 3) Silver NPs are widely used in animal health for veterinary medicine, animal health, and animal production; 4) Over 10 countries around the world are currently using various types of nano-enabled products for crop protection and in AHs. It was found that one of the main limitations in the meta-analysis was the toxicity of products enabled by NPs. This does not necessarily mean that these interactions between plants, animals, and NPs are entirely negative.

However, it is important to monitor them closely, and future meta-analyses may be required to assess the toxicity levels of commercially nano-enabled products currently being used for crop production, protection, and AHs.

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