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Harnessing humic acid: cultivating sustainable agriculture and environmental resilience in pursuit of SDG's

Bunga Enosh[1], **Anita Jaswal***,

[1]*Department of Agronomy, School of Agriculture Lovely Professional University, Phagwara 144 411(Punjab), India
†**Corresponding author** e-mail – anita.27139@lpu.co.in, jasanita91@gmail.com

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ABSTRACT
Through a variety of processes, humic acids (HA) contribute immensely to the growth of plants and the improvement of soil health. The organic molecules known as HA are formed from organic materials, coal, and soil. They have a good impact on plant development, nutrient availability, and soil qualities. By boosting nutrient uptake, especially of micronutrients, through chelation and co-transport mechanisms, HA promotes plant growth. Additionally, they raise the solubility of nutrients and lower the pH of the soil, which can raise the availability of nutrients. HA promotes plant growth, which enhances crop growth, and supports hormones that help with stress tolerance, nutrition, metabolism, and photosynthesis, including auxin and cytokinin. Due to the formation of micelles by HA, which improve clay aggregate stability and resist water molecules, soil water-holding capacity (WHC) can be increased. Field crops benefit from humic acids because they improve soil qualities, nutrient availability, and crop growth, which increases yield and quality. To completely comprehend the mechanics and maximize the use of HA in crop production, more research is necessary. To observe the role of humic substance on different crops and their growth.

KEY WORDS: Humic acid, Vermicompost, Growth Parameters, Soil Health and sustainability

1. INTRODUCTION:

Humic substances are organic compositions that have a brownish or blackish appearance, huge molecular weights, and complicated structures that are formed by the breakdown of plant or animal remains. Additionally, it has been added to soil as an amendment to improve its chemical and physical properties. Humic compounds can be soluble at different pH levels; they include fulvic acid, humin, and humic acid. Empirical evidence suggests that humic materials, irrespective of their kind, origin, or characteristics, generally enhance plant yields, seed germination, and physio-chemical characteristics and either directly or indirectly stimulate root absorption.

According to Nardi *et al*.,2002 humic acid may have a direct impact on processes involved in plant growth, including respiration, photosynthesis, cell elongation, and permeability. Other studies have demonstrated the effects of humic compounds on fruits and vegetables (Arancon *et al*., 2006; Pilanal and Kaplan, (2003); Delfine *et al*., 2005; Jones *et al*., 2007; Lolium perenne Verlinden *et al*., 2010; Tuefenkci *et al.*, 2006; Yildirim, 2007. Plant disease incidence decreased as a result Naidu *et al*., (2013); Olivares *et al*., (2015); Singh *et al*., (2010). Apart from the significant alterations in food absorption and primary metabolism in plants, humic chemicals may also have a significant impact on secondary metabolism. Schiavon *et al.*, 2010; Canellas *et al*. (2015). Humic, fulvic acids, and humic acids are the three types of HS based on their solubility in aqueous, acidic, or alkaline solutions, respectively. Because the humic percentage in HS does not degrade, researchers have concentrated on the HA and FA fractions because they can quickly improve soil fertility and health. Because of their chemical reactivity and resistance to microbial processes, the HA and FA portions of HS are advantageous to plants and soils (Billingham, 2012). The long-term degradation resistance and amphiphilic characteristics of HA allow complex cations to develop Wood, (1996). About 60% of the HA fraction is organic carbon (C), which is crucial for the development of soil microorganisms Sible *et al*., (2021). HA also contains nitrogen (N), oxygen (O), hydrogen (H), and sulphur (S) in addition to C. Humic acids improve the structure, texture, water-holding capacity (WHC), and microbial population of soil, which increases the physical and biochemical activity of the soil Narid *et al*. (2021). By chelating and co-transporting micronutrients to plants, it raises the availability of nutrients in the soil, particularly micronutrients Yang *et al*., (2021). By boosting plant growth-promoting hormones like auxin and cytokinin, which support stress tolerance, nutrient metabolism, and photosynthesis, humic acids also promote crop development

(Canelass *et al*., 2020). According to a recent analysis by Nardi *et al*. (2021), the chemical and molecular structures, sources, and application rates of HA are significant determinants in determining how it impacts crops and soil. Importantly, different yield results may arise from the administration of HA, possibly as a result of its various biological sources Sible *et al*., (2021). Given the contradictory outcomes of HA application on crop agronomic performance, which can be attributed to variations in HA sources and experimental setups, as well as the dearth of research on field experiments relative to laboratory trials, this review aimed to comprehend HA application in agricultural production.

Natural organic matter (NOM) is a byproduct of the decomposition of plant and animal tissues and plays a crucial role in the global carbon cycle along with the biota. Thousands of years of on-farm observation and experimentation, together with the findings of more than a century of contemporary agricultural research, support the association between NOM and crop productivity. The crucial impact of NOM on the characteristics, activities, and functions of soil forms the basis of this relationship. The NOM that makes up to 80% of soil organic matter is called humus, or HS for short. It is acknowledged that Humic substance (HS) play a crucial role in supporting plant growth due to their positive impacts on the biological, chemical, and physical characteristics of soil. In a naturally varied soil environment, the root system is essential to a plant's ability to absorb water and nutrients, alter its rhizosphere for to enhance nutrient mineralization, and choose its microbiological community. It is possible for HS to influence these processes. Given that HS creation has a dramatic impact on the genesis and soil usage history, it is not surprising that HS can alter plant root architecture and growth. Plants began to use H^+ as the master ion during the conquest of land, when salt stress disappeared. Rich in organic matter, vermicompost provides plants with sufficient amounts of humic compounds and nutrients. It is created by the activity of several earthworm species, including *Eisenia hortensis* and *fetida,* among others. Micronutrients, including iron, zinc, copper, and other elements, are absorbed by organic acids created during the vermicompost digestion process and then made available to plants. Vermicompost has a high water-holding capacity, so it always supplies enough water to keep plants from experiencing severe water shortage stress. The primary concept behind the cultivation of therapeutic plants is the organic cultivation of superior crops. In order to meet the nutritional needs of farmlands, it is now more crucial than ever to use organic fertilizers and bio stimulants.

2. MODE OF ACTION OF HUMIC ACID:

2.1 Nutrient uptake: In soil applications Humic acids increase the availability of nutrients in soil that might not otherwise be present. The organic makeup of the acids comes first. Because humic acids oxidize naturally, they have a net negative charge. Positive ions, or "cations," are drawn to these large molecules and attach to them as a result. Humic acids possess a special and extremely advantageous property known as "cation exchange capacity." Furthermore, a large number of the nutrients that plants require, including calcium, iron, magnesium, and other trace minerals, have a positive charge. Thus, these nutrients come out of the soil and bind to humic acids when humic acids are present. After that, they can be moved close to the plant's roots. In addition to the humic acid, the root systems have a greater negative charge. In order for the plant to absorb the humic acid, the positive ions attached to it must be released. Many of the nutrients that are designed to fertilize plants would stay locked in the soil without the help of this essential mechanism. Where as in foliar application Humic acids have advantages outside of soil use. They work well in foliar treatments when combined with shorter-chain organic compounds called fulvic acids. Plants need humic acids to increase the permeability of their cell walls. Nutrients can enter a plant more readily when cell membranes become more permeable. Fulvic acids, which are particularly effective chelators, are frequently responsible for this process The researcher conducted an experiment on maize plant he concluded that improves the microbial activity in costal saline soils and integrated growth was observed by applying of Humic acid and Vermicompost Liu, Mengli *et.al*, (2019)

2.2 2Reduced toxins: Not only humic acids increase the availability of nutrients, additionally, they block toxic substances from penetrating the plant by chelating them in the soil. This benefit is especially significant in the soil settings of today, when heavy metals and pesticides are only two of the many pollutants that have been introduced over many years. These pollutants damage soil quality, and they will keep deteriorating crop health and volume in the absence of appropriate rehabilitation. Humic molecules ensnare and imprison these harmful chemicals. They are not absorbed by the plants, in contrast to nutrients, and are eventually washed out. This essential mechanism maintains plant health in the increasingly demanding growing conditions of today the findings of an experiment carried out by a researcher revealed that VC amendment is useful in lowering the availability of potentially hazardous metals in tropical acidic soils that are both polluted and artificially spiked. The lower availability of Cd, Ni, and Cr in the contaminated soil is probably due to the adsorption of metals onto VC and a rise in soil pH following VC amendment Liu, (2019).

2.3 Water retention: By chelating harmful compounds in the soil, humic acids not only make nutrients more readily available to plants, but they also prevent them from entering the plant. This is particularly important given the soil environments of today, where pesticides and heavy metals are just two of the numerous pollutants that have been introduced over a long period of time. In the absence of suitable rehabilitation, these contaminants will continue to degrade crop health and volume and harm soil quality. These dangerous substances are ensnared and imprisoned by humic molecules. Unlike nutrients, they are not taken by the plants and are eventually washed out. In the more demanding growing conditions of today, this vital function keeps plants healthy.

2.4 Microbial growth: The effect of humic acids on soil microbial populations is one of its most obvious and significant advantages. Researchers are becoming more and more aware of the significance of a robust microbiome for soil habitats. Furthermore, it's critical to reestablish the various bacterial communities that have been severely reduced by pesticides and poor soil quality. Humic acids help microbial communities grow in two ways. They first supply carbon, which acts as a food source for microorganisms. Secondly, because of their size, they offer a place for microflora to settle. That's why microbial communities thrive in the presence of humic acids; essentially, humic acids give food and shelter to helpful microorganisms. *Rhizobium* and humic acid-rich vermicompost work together to improve soil fertility by enhancing microbial diversity and abundance, plant growth, and soil enzyme activities. This could lead to the development of new techniques for producing higher agricultural yields in an environmentally and organically friendly way. Deepamala Maji, (2017) in her experiment she concluded that application of vermicompost improves microbial activity and yield of plant growth increased.

2.5 Soil structure: Humic acid has both positive and negative charges, despite having a net negative charge. Furthermore, its molecular size is enormous. These characteristics allow humic acids to attach themselves to various types of soil particles, providing the essential room for microorganisms and strong root development. In compacted and high-clay soils, where soil particles are closely linked together, this is particularly apparent. Clay particles can even be made to stand on edge by humic molecules, which increases the amount of available space and water penetration. Moreover, they eliminate salts from clay, which gives the clay particles a negative charge again and pushes them apart. In summary, vermicompost and humic acid fertilizer can ameliorate saline-alkali soils by replenishing organic matter, improving aggregate microstructure, and regulating the microbial growth, which could increase salt leaching and inhibit nitrogen losses (M. Liu, 2020) In his experiment he concluded that by restoring organic matter, vermicompost and humic acid fertilizer were able to modify the microstructure of macroaggregates, improving salt leaching and controlling the microbial community in the soil. Enhancing the aggregate microstructure has the potential to reduce nitrogen loss and boost nitrogen availability in saline-alkaline soil by controlling N-cycling bacteria. Moreover, vermicompost demonstrated a significant contribution to lowering soil salinity, whereas humic acid also.

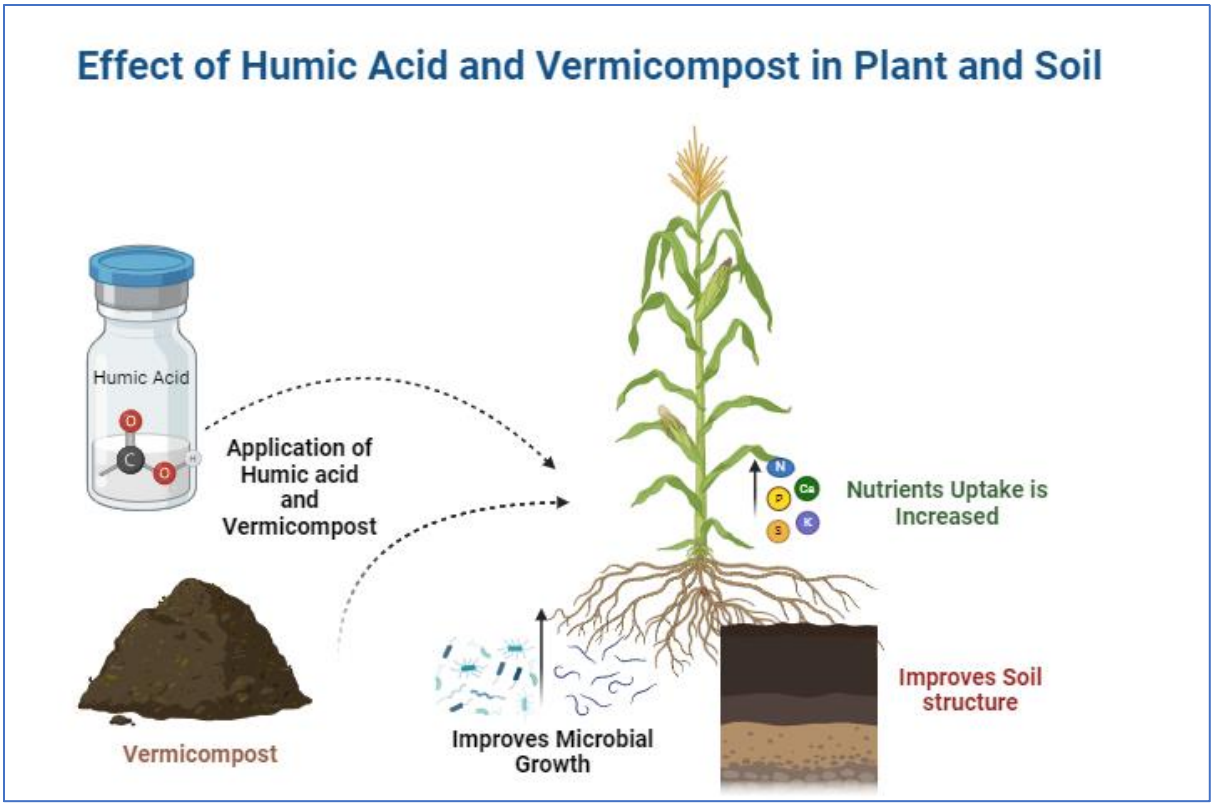

Fig.1 representing effect of humic acid and vermicompost on plant and soils

3.INFLUENCE ON PLANT GROWTH:

3.1 Root Development: Plant root development can be positively impacted by humic acid through a number of factors including: By Better Soil Structure it promoting soil aggregation, humic acid improves soil structure. Root penetration and expansion are made easier by this improved structure, which encourages healthy roots and enhanced Nutrient Availability of Plant roots may access vital nutrients in the soil more readily when humic acid chelates them. This can result in larger and healthier root systems by guaranteeing that roots have access to a constant supply of nutrients needed for growth and development also Stimulation of Root Growth that Research has demonstrated that humic acid directly stimulates root growth by encouraging the division and elongation of cells in root tissues. As a result, roots get longer and more biomass. Allowing plants to explore a large volume of soil of water and nutrients and Improved Capture of Water Through an increase in soil porosity and water-holding capacity, humic acid enhances soil water retention. Sufficient soil moisture is essential for the establishment of roots, and increased water retention can promote larger and deeper root systems. Induction of Hormonal Responses like Auxins, which are important for root development, are one type of hormone that humic acid can affect in plants. Humic acid can increase the synthesis and activity of auxins, which can strengthen root systems by encouraging root branching and elongation. All things considered, humic acid administration can lead to improved root development, which is typified by increased root biomass, length, branching, and general health. These advantages help plants absorb nutrients and water more efficiently, anchor themselves better, and become more resilient to environmental challenges, all of which result in healthier plants in the long run. After conducting an experiment on root development, a researcher found that the presence of aromatic compounds in humic acid was related to root growth stimulation activity, while aliphatic and oxygenated structures in humic acid water extract showed a relationship with the induction of initial root emissions. In comparison to humic acid, a higher concentration of humic acid water extract was required to produce an equivalent stimulus. This finding suggests that while the composition of both fractions displayed similar types of structures, the predominant structures may be influencing the root's response differently Garcia., (2018).

3.2 Stress Tolerance: When there is no stress on the plant, vermicompost has been shown to have positive impacts. A couple of recent research have emphasized the role of vermicompost as a stress modulator. In an experimental study on sodium salt stress in soil, vermicompost was found to be an excellent soil conditioner that also reduced the harmful effects of sodium in soils that were stressed by Na salt. Physicochemical properties of the soil were enhanced by treating it with vermicompost at varying salinity stress levels. Treating the soil with vermicompost improved its quality while effectively mitigating the negative impacts of salt. The restoration of soils affected by Na salt has demonstrated the effectiveness of vermicompost as an ameliorating material Demir (2020).

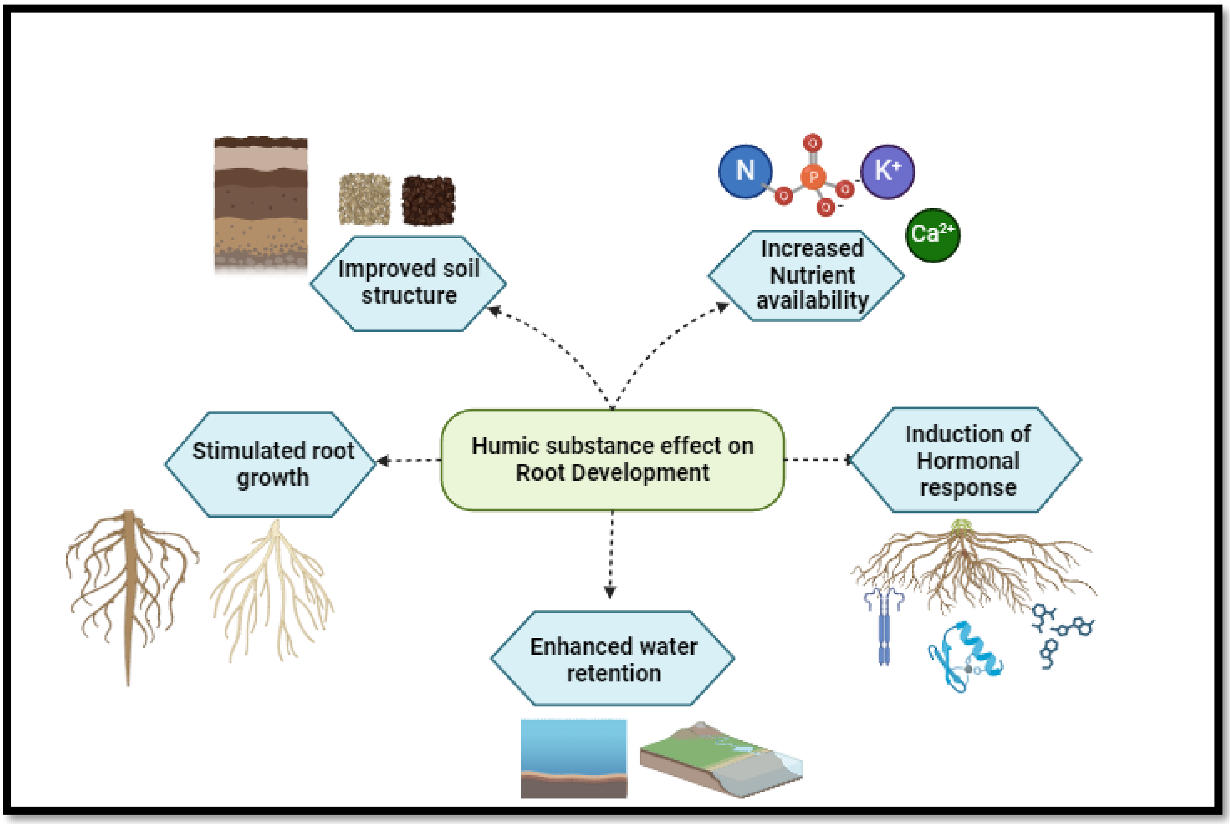

Fig 2 indicating the effect of humic substances on root development

4.IMPACT ON SOIL HEALTH:

4.1 Soil Fertility Enhancement: In addition to providing vital nutrients for agricultural plant growth, healthy soil also has a characteristic soil structure, a diversified and active biotic community, and it permits undisturbed decomposition. The top soil, subsoil, and parent material are its three layers. However, since the top soil is what promotes plant growth, we are more interested in it. To be considered fruitful soil, a certain combination of minerals, air, water, living things, and inorganic and organic matter must be present in a certain ratio and have a pH of at least medium (Alizadeh., 2018) The indirect effects of humic compounds on soil fertility include:

- Increase in the soil microbial population including beneficial microorganisms
- Improved soil structure
- Increase in the cation exchange capacity and the pH buffering capacity of the soil

4.2 pH Regulation: Both humic acid and vermicompost can affect the pH of soil, but how much and how often they are applied, as well as the particular qualities of the humic acid or vermicompost being used, can all have an impact. As a soil conditioner, humic acid is commonly added to soil after organic matter has broken down. Since it often has a low pH, applying it to the soil may initially cause the pH to drop. But over time, humic acid can also function as a buffer, assisting in the stabilization of soil pH and averting sharp variations. Furthermore, humic acid can raise the soil's cation exchange capacity (CEC), which influences nutrient availability and consequently affects pH. The pH of vermicompost, which is created when earthworms break down organic materials, is often close to neutral. The addition of vermicompost to soil has the potential to promote microbial activity, improve soil structure, and increase nutrient availability. Vermicompost alone may not have a big impact on the pH of the soil, but over time, its effects on soil health may indirectly affect pH levels. The interactions that humic acid and vermicompost have with the soil and the particular circumstances under which they are applied will determine their overall impact on the pH of the soil. Generally speaking, both can support the soil's general fertility and health, which can support the maintenance of pH values that are ideal for plant growth. When applying these amendments, it is crucial to periodically check the pH of the soil and modify the amount used in order to maintain the pH within the range that is ideal for a given crop or plant. In a barley-grown pot experiment with different HA application and post-harvest soil pH analysis showed a decreasing trend in pH with increased humiliate rates Lakosky *et.al,* (2020) Peanut cropping system involved in continuous 3 years, HA application did not significantly affect soil pH Li *et.al,* (2019).

4.3 Soil Erosion: Through a number of methods, the use of vermicompost and humic acid can help reduce soil erosion. Enhanced Soil Structure By promoting aggregation and stability, vermicompost and humic acid can both strengthen the structure of soil. This change in soil structure lowers surface runoff while raising soil porosity and water penetration rates. As a result, the soil is less vulnerable to water erosion. An Increase in Organic Matter in the Soil Vermicompost and humic acid are excellent providers of organic matter. By adding more organic matter to the soil, they strengthen the bonds that hold soil particles together and prevent erosion and separation from wind and water. Increased Fertility of Soil Essential nutrients are added to the soil via humic acid and vermicompost, which encourages healthy plant growth. Erosion risk can be decreased by having stronger, healthier plants with denser, deeper root systems that can anchor soil more successfully. Decreased surface crusting Compaction and the effect of raindrops can cause surface crusts to form on soil, which can be lessened by using humic acid and vermicompost. Surface crusts have the potential to worsen erosion by blocking water infiltration. Humic acid and vermicompost have the ability to improve soil structure and increase soil organic matter content, which can help inhibit the formation of surface crusts and minimize erosion. Microbial Activity Vermicompost and humic acid both encourage microbial activity in soil. In the processes of soil stability and aggregation, microorganisms are essential. They enhance soil structure and lessen the soil's vulnerability to erosion by aiding in the binding of soil particles together. All things considered, the use of vermicompost and humic acid can support sustainable soil management techniques that lessen soil erosion. For thorough erosion prevention tactics, it's crucial to take into account additional erosion control techniques such as contour ploughing, terracing, and vegetation buffers in addition to organic soil additives. Moreover, the addition of organic matter decreased soil separation, water runoff, and the movement of NH^{4+} and NO_3^- into water. When vermicompost was used instead of compost and buffalo dung, these benefits were more pronounced. Thus, one of the study's main findings is that vermicompost has many positive effects beyond only improving plant growth and productivity (Doan, 2015)

4.4 Soil Borne Diseases: Through a number of methods, humic acid and vermicompost can be beneficial for diseases that are transmitted through the soil. Vermicompost and humic acid both include compounds that have been demonstrated to inhibit soil-borne diseases. For example, humic compounds have been shown to change the composition of the microbial community and increase the antagonistic activity of beneficial bacteria, thereby inhibiting the growth and activity of several soil-borne diseases. Increased Microbial Activity in the Soil Beneficial soil microbial populations, such as fungi and bacteria, can be increased by humic acid and vermicompost. These microorganisms compete with and oppose soil-borne diseases. By colonizing the rhizosphere and creating a barrier against pathogenic intruders, these advantageous bacteria can lower the prevalence of diseases carried by the soil.

4.5 Activation of Plant Défense Systems Vermicompost and humic acid have both been shown to strengthen a plant's defences against infections. Plants' immune responses can be strengthened and antimicrobial chemicals produced as a result of their induction of defence-related gene expression. Plants with this systemic resistance may be more resilient to infections carried via the soil. Direct conflict engagement Certain components of vermicompost and humic acid may have direct antagonistic activity against soil-borne diseases, according to certain research. These elements could consist of bioactive substances, organic acids, and enzymes that stop the spread of infections or interfere with their life cycles. Although vermicompost and humic acid can help reduce soil-borne illnesses, it's vital to remember that their efficacy may differ based on things like: in an effort to improve the quality and quantity of tomato fruits, a researcher managed the incidence of tomato root-rot disease by experimenting with vermicompost and humic acid. From rotten tomato root samples, *Fusarium oxysporum, F. solani, Pythium sp*., *Rhizoctonia solani*, and *Sclerotium rolfsii* were identified by Mohammed F.A. (2022). Ultimately, he came to the conclusion that vermicompost lowers the disease indices in the soil.

5.APPLICATION TECHNIQUES AND RECOMMENDATIONS:

5.1 Application rates and timing: After two years of application, the humic product's advantages for soil characteristics and plant growth in field settings were demonstrated. With no effect on the interval (months) between treatments, a single application at the start of each growing season yielded better results than two applications. Compared to the control, a single treatment greatly enhanced soil accessibility for potassium by 96% and phosphorus by 63% (Yihan Z, 2022). Humic acid can be sprayed at any point during the growth season, as foliar sprays, at planting, or even before planting. While in-season applications can continue to improve soil fertility and plant health, pre-plant applications enable absorption into the soil prior to planting. Increased maize yield can be achieved by using organic fertilizers like compost and vermicompost made from chicken faces. The production is impacted by the timing of these fertilizers' applications. When the vermicompost is spread out prior to seeding, the best yield and yield qualities are achieved (Sifolo.S, 2020). Vermicompost can be added to the soil as a top dressing during the growing season, mixed into the soil during bed preparation, or applied as a soil supplement prior to planting. The vermicompost's degree of decomposition may also affect when to apply it; fully composted vermicompost is typically recommended to prevent nitrogen immobilization and General considerations are also followed they are.

Soil Testing: To determine the current nutrient levels, pH, and organic matter content of the soil, it is important to perform a soil test prior to applying humic acid or vermicompost. The results of soil tests can be used to detect specific nutrient imbalances or deficiencies that need to be corrected, as well as to help calculate the right application rates.

Crop Stage: When determining when to apply vermicompost or humic acid, take the crop's growth stage into account. While mid-season or post-harvest treatments may help certain crops build robust root systems and increase soil fertility in preparation for later plantings, early-season applications may be more advantageous for other crops.

Environmental Conditions: When determining the best time for an application, take into account elements like the availability of moisture and the weather. When there is a lot of rain or a drought, don't add humic acid or vermicompost; the right soil conditions will help plant growth.

Integrated Approach: To optimize their effects and support long-term sustainable soil health and fertility, humic acid and vermicompost should be included in an integrated soil management strategy with other techniques including crop rotation, cover crops, and limited tillage.

5.2 Integration with conventional farming: For organic farming, vermiculture or vermicompost can be the best option. Vermicomposting can have a significant impact on crop yields as well as germination, growth, flowering, and fruiting. Applying vermicompost improves soil health, minerals, water-holding capacity, soil microorganisms, yields crop nutritional benefits, and lowers populations of plant pests (Mistry, 2015). Decreased Reliance on Artificial Inputs In conventional farming, crop nutrient requirements are usually met mostly by synthetic fertilizers. Farmers can lessen their reliance on synthetic inputs by using vermicompost and humic acid. Vermicompost enriches the soil with organic nutrients and helpful bacteria, while humic acid offers a natural source of organic matter and minerals. Farmers may save money as a result of this decrease in their reliance on synthetic inputs, which also lessens the environmental effects of using chemical fertilizers. Better Cycling of Nutrients

In the soil-plant system, humic acid and vermicompost improve nutrient cycling. Humic compounds included in humic acid facilitate the availability and uptake of nutrients by plants, whereas vermicompost releases nutrients gradually during its decomposition process. This lowers the possibility of fertilizer runoff or leaching and increases nutrient efficiency. Improved yield of crops Integrating humic acid with vermicompost can improve crop performance and yield quality in conventional agricultural systems. With their organic matter, beneficial bacteria for plants, and bioactive compounds, humic acid and vermicompost can boost a plant's tolerance to environmental stressors, including disease, pests, and drought, while also promoting root growth and improving nutrient uptake. Improved yields and more marketable quality can result from crops with greater vigor and vitality. Advantages for the Environment Conventional farming practices that incorporate humic acid and vermicompost can benefit the environment. By enhancing soil health and fertility, these organic additives reduce soil erosion, reduce greenhouse gas emissions, and conserve water resources. Furthermore, the reduced reliance on artificial inputs may contribute to a reduction in the carbon footprint and sustainability of agricultural production. So, incorporating vermicompost and humic acid into traditional agricultural methods provides a comprehensive strategy for managing soil that encourages resilience, sustainability, and production. Farmers may increase soil health, lessen their influence on the environment, and produce more sustainable agricultural results by utilizing the advantages of these natural soil additives.

5.3 Complementary amendments and practices: When included in farming systems, a number of supplementary amendments and practices in addition to humic acid and vermicompost can further improve soil health and agricultural output. Here are a few instances:

Cover Crops: During fallow seasons or in between cash crops, planting cover crops, such as legumes or grasses, can help enhance soil structure, control weed growth, lessen erosion, and enrich the soil with organic matter when mulched or integrated. This critical worldwide assessment and systematic analysis set out to evaluate cover crop techniques in relation to agricultural production, nitrogen leaching, and net greenhouse gas balances (NGHGB) (Mohamed.A, 2019) The study only included studies that examined the effects of cover crops and assessed one or more of the following: nitrogen leaching, soil organic carbon (SOC), nitrous oxide (N_2O), grain yield, and nitrogen in the grain of the primary crop, along with a control treatment.

Crop rotation: Changing up the roots and nutritional requirements of crops can disrupt the cycles of pests and diseases, increase soil fertility, and lessen soil erosion. Legumes are among the crops that have the ability to fix atmospheric nitrogen, adding this vital nutrient to the soil.

Mulching: When organic mulches, such as straw, compost, or shredded leaves, are applied to the soil's surface, the mulch helps to retain moisture, inhibit weed growth, control soil temperature, and gradually release organic matter into the soil as it breaks down. Reduced or no-till tillage: Reducing soil disturbance by using these techniques protects soil structure, raises soil organic matter, lowers erosion, and improves water infiltration. In addition to assisting in the retention of soil moisture and carbon sequestration.

Compost Tea or Extracts: Fermenting compost tea or extracts from decomposed organic materials can yield a liquid form of nutrients, humic substances, and helpful microorganisms that can be sprayed on crops as a foliar spray or incorporated into the soil to enhance soil health and promote plant growth.

Biochar: By adding biochar, a stable form of organic matter rich in carbon that is created by pyrolysis, to the soil, you can enhance its microbial activity, water retention capacity, and structure. Additionally, biochar may be able to store carbon in the soil for extended periods of time, slowing down global warming. In order to maintain crop productivity and sequester more soil organic carbon than vermicompost, it would be preferable to introduce biochar into the fertility program of the wheat-green gram crop cycle in addition to inorganic fertilizers (B. Sarma, 2018) After applying biochar, the amount of nitrogen available in the soil was observed, indicating environmental sustainability.

Microbial Inoculants: Applying microbial inoculants containing mycorrhizae, fungi, or beneficial bacteria can improve soil structure, reduce diseases that are carried by the soil, optimize nutrient cycling, and encourage plant development and stress resistance. According to the current study's findings, adding rhamnolipid, P. chrysosporium, and A. chrococcum together increased both the vermicompost's quality and overall efficiency. This ideal mixture accelerated the breakdown of lignin and cellulose, raised the concentrations of nutrients in the vermicomposts, raised microbial counts and enzymatic activity, while also enhancing E. fetida growth and fecundity during vermicomposting. Additionally, the combination produced a vermicompost with physical properties within ideal ranges for use in agriculture. Based on these findings, we propose that adding rhamnolipid, P. chrysosporium, and A. chrococcum together can improve the vermicomposting of green waste (Gong, 2017).

5.4 Integrated Pest Management (IPM): By combining chemical, biological, and cultural control techniques, IPM strategies can help manage pests and diseases in a more sustainable way while reducing the need for synthetic pesticides. Regular soil testing aids in determining the pH and fertility of the soil, which enables focused nutrient inputs based on crop requirements. The danger of overfertilization, nutrient runoff, and environmental contamination is decreased with precision nutrient management. Through the integration of complementary amendments and practices, together with the use of vermicompost and humic acid, farmers may establish more robust and sustainable farming systems that prioritize soil health, optimize crop productivity, and reduce their environmental footprint.

6. CASE STUDIES: -

Research Findings: - Junaid *et al*. (2020) conducted a field experiment on wheat to examine the effects of plant spacing and foliar nutrition with four concentrations of humic acid on barley growth and yield. He found that the treatment was significantly better than the control, with the highest values in the majority of yield parameters, including the number of spikes per square meter, the number of grains per spike, the yield of grains, the biological yield, and the harvest index. An Experiment was conducted by Kavya *et al*, (2018) on maize crop to observe effect of humic acid in salt affected soils and concluded that the effective improvement of salinity tolerance in maize plants through exogenous application of HA can be related to the increase in plant biomass, chlorophyll levels, mineral nutrients, and activity of important antioxidant enzymes induced by HA. Saruhan *et al*, (2011) studied on common millet regarding organic matter, a vital but dynamic component of soil, affects the various chemical, physical, and biological characteristics that control soil production. The goal of applying humic chemicals to plants is to enhance common millet yield performances, improve herbage and protein production, and balance vegetative and reproductive growth. The study's findings indicate that humic acid treatments increased yield and yield components, and this boosting was discovered. Daur *et al*., (2014) observed in pearl millet that the study's findings showed that raising the amount of HA to a specific level (20–25 kg ha^{-1}) consistently and significantly ($p<0.05$) enhanced plant growth in terms of plant height, leaf count, leaf area index (LAI), and yield of dry matter and green matter. The chemical examination of the crude protein and mineral content further supported the increased growth. HA to the soil to increase the quality and productivity of millet crops in saline and dry environments and by increasing the amount of nitrogen in the soil and improving millet's ability to absorb nutrients, humic acid treatment promoted crop growth and the generation of dry matter. Furthermore, a comparison between the control and specific HA treatments' outcomes demonstrates that humic acid is a useful organic source that may be utilized to keep soil fertile and reduce salinity. This study showed that the extra benefit of applying foliar humic acid to maize under 2:2 row intercropping with soybeans was a 50% reduction in nitrogen fertilizer usage, production costs, and pollution while also increasing growth, yield, and chemical constituents studied by Amina *et al*, (2016).

Table 1. Effect of Humic acid on different crops

Crop	Effect of HA	Reference
Common millet (*Panicum miliacium*)	Improved Herbage and protein production Balanced vegetative and reproductive growth	Saruhan *et al.*, 2011
Bajra (*Pennisetum glacum*)	Improved Leaf area index (LAI), yield of dry matter and green matter Increased amount of Nitrogen in soil, keeps soil fertile and reduced salinity	Daur *et al.*, 2014
Maize and soyabean (2:2 inter cropping)	Reduced Nitrogen cost 50%.	Aman *et al.*, 2016
Maize (*Zea mays*)	Improved from salt affected soils Increased chlorophyll and mineral nutrients, antioxidants, enzymes induced.	Kavya *et.al*, 2018
Wheat (*Triticum aestivum*)	No. of spikes per sq. Meter increased	Junaid *et.al*, 2020

Table 2. Impact of Humic acid on crop yield.

Crop	Dosage of HA	Grain Yield (Increased over control plot)	Reference
Wheat (*Triticum aestivum L.)*	2g L^{-1}	159.5%	Abou-Aly and mady, 2009
Rice (*Oryza sativa L.)*	6L ha^{-1}	71.7%	Saha *et al.*, 2013
Mungbean (*Vigna radiata L.*)	3kg ha^{-1}	72%	Waqas *et al.*, 2014
Lentil (*Lens culinaris L.*)	300kg ha^{-1}	24.15%	Dogan *et al.*,2014
Chickpea (*Cicer arietinum L.)*	9kg ha^{-1}	34%	Kahraman 2017
Sunflower (*Helianthus annuus L.)*	4Lha^{-1}	6.1%	Hatami 2017
Barley (*Hordeum vulgare L.*)	500mg $^{-1}$L	54.2%	Dulaimy and El-Fahdawi 2020

7.CHALLENGES AND FUTURE PERSPECTIVES: -

7.1 Quality control and standard action: Products containing humic acid might differ greatly in terms of quality and purity. Products of poor quality could be contaminated or fail to deliver the promised advantages. Purchasing premium humic acid goods from reliable vendors is essential. It can be difficult to determine the right humic acid administration rate. While insufficient amounts might not have the intended effects, excessive amounts can cause nutritional imbalances or even poisoning. It takes careful evaluation of variables including crop variety, soil type, and current nutrient levels to find the proper balance. Product lines containing humic acid might not always mix well with other agrochemicals, fertilizers, or soil additives. Before applying, compatibility testing should be done to make sure there won't be any negative impacts on plant development or soil quality. Although humic acids (HA) are widely used as a soil additive to lower metal availability, they have two disadvantages: they gradually lose their potency and cause the pH of the soil to significantly drop. To get around these problems, an alkaline humic acid fertilizer (AHAF) that combines HA with alkaline additions was created Fan Q *et.al,* (2023). Humic acid can be applied in a number of ways, such as through seed treatment, fertigation, foliar spraying, and soil incorporation. Numerous factors, like crop variety, soil conditions, and equipment availability, influence which method is best. Every technique has its own unique considerations and difficulties.

7.2 Environmental causes: The efficiency of humic acid can be affected by environmental factors such as pH, temperature, moisture content, and microbial activity in the soil. Depending on the particular formulation and application technique employed, different circumstances may be ideal. Products containing humic acid may be more costly than those containing other fertilizers or soil additives. To assess if an application is economically feasible, farmers must consider the possible advantages against the expense of implementation. Although humic acid has some short-term advantages, research is still being done on how it affects soil fertility and health over the long run. If humic acid is used excessively or continuously without adequate management and monitoring, it may have unforeseen effects such nutritional imbalances or modifications to the microbial populations in the soil. Instead of using qualitative tests to assess and concentrate on "the quality" of the product in the bottle, nearly all government testing and registration processes worldwide use quantitative humic acid tests to ascertain "how much" humic fulvic acid is in the bottle. Consequently, it makes sense that retailers and growers would be perplexed, especially when examining crop data. While applying considerably larger volumes of a low-grade humic fulvic acid product won't have the same effect, using tiny amounts of high-quality humic fulvic acid can produce extremely good crop results. Heavy metals may be adsorbed by HAs, which would lessen their toxicity and mobility in the environment. Additionally, HAs may aid in the degradation of microplastics and aid in the adaption to climate change Pengfei Xu *et.al,* (2022). Regulating or prohibiting the use of humic acid in agriculture may depend on the location. Farmers are responsible for making sure that the applicable laws and rules controlling the use of agrochemicals and soil amendments are followed. Planning, observing, and managing humic acid carefully is necessary to optimize its benefits and minimize any dangers to agricultural yield and environmental sustainability.

7.3 Future innovations and research direction: The purpose of this report is to give readers a thorough overview of the global market for humic acid, complete with quantitative and qualitative analysis, so they can create growth and business strategies, evaluate the competitive landscape, assess their place in the market, and make well-informed decisions about their business Humic acid global outlook 2023 to 2029. The goal of ongoing research on humic acid application in agriculture is to better understand its mechanisms of action, increase its efficacy, and find novel uses for it. Here are a few possible advances and future research possibilities in this area. To precisely understand how humic acid interacts with soil, plants, and microbes, more research is required. This entails researching its molecular effects on plant physiological systems, microbial communities, soil structure, and nutrient availability. Subsequent research endeavours may concentrate on creating innovative humic acid formulations that exhibit improved stability, bioavailability, and tailored delivery mechanisms. Studying cutting-edge application strategies like precision farming or nanotechnology-based delivery systems could maximize their effectiveness and reduce their negative effects on the environment. Canellas, L *et.al,* (2002). Integrated nutrient management solutions for improving soil fertility and crop productivity may result from research into the synergistic effects of humic acid combined with other soil amendments, fertilizers, or biofertilizers. Farmers and policymakers may find useful information by conducting economic assessments to assess the cost-effectiveness of humic acid application in various agricultural systems and geographical areas. Ensuring product efficacy and consumer confidence requires the development of regulatory frameworks and guidelines, including quality standards, labelling requirements, and environmental restrictions, for the safe and sustainable use of humic acid in agriculture. By combining the application of humic acid with precision agriculture technology, such soil sensors, remote sensing, and variable rate application systems, its use could be optimized according to crop and soil conditions specific to each location. In order to ensure sustainable agricultural operations, it is imperative to evaluate the environmental repercussions of humic acid application, including its effects on greenhouse gas emissions, soil biodiversity, and water quality.

8. CONCLUSION:

In conclusion, because of HA diverse impacts on soil structure, nutrient availability, microbial activity, and plant physiological processes, humic acid is essential for promoting plant development and enhancing soil health. Humic acid enhances soil fertility, water retention, and aeration by chelating minerals, increasing cation exchange capacity, and encouraging soil aggregation. This creates an environment that is favourable for root development and nutrient uptake. Furthermore, humic acid promotes advantageous relationships with soil microbes, improving disease prevention, nutrient cycling, and general biological activity in the soil. Humic acid functions as a bio stimulant in plants, promoting root development, boosting nutrient absorption, and strengthening stress-resistance systems. Increased photosynthesis, hormone regulation, and antioxidant activity are some of the effects it has on plant physiology, which improves growth, yield, and quality of crops. Although humic acid has long been known to have advantages in agriculture, more study is still required to fully understand how it works, determine the best ways to apply it, and determine how it will affect soil fertility and environmental sustainability in the long run. Farmers may increase crop yield, lessen their reliance on artificial inputs, and strengthen the resilience and health of agricultural ecosystems by incorporating humic acid into sustainable soil management techniques.

AUTHOR CONTRIBUTIONS

All the authors wrote, reviewed, and approved the final version of the manuscript equally.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest

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