



## Speciality fertilizers in agriculture: An overview

Hugo Opperman

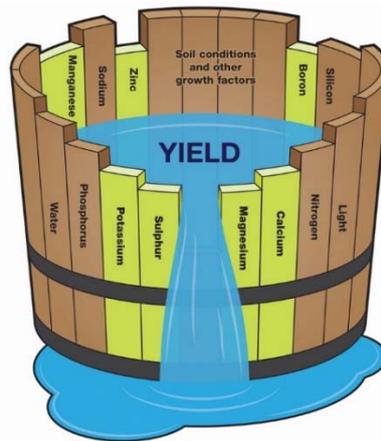
Head chemist – MBFi

### Abstract

As a result of diminishing agricultural land and a growing world population, the need for more specialized agricultural practices has arisen. One approach to improve crop cultivation, is the use of more specialized fertilizer practices/products. Specialized fertilizers have the ability to significantly increase crop yields, by using a more targeted approach. A better understanding of plant physiology and plant interactions with its environment have led to the development of fertilizers that optimizes specific growth stages, metabolic functions and the ability of a plant to cope with certain stress conditions. Three main classes of speciality fertilizers have been identified: i) Nutrients, ii) biostimulants and iii) biological fertilizers/stimulants. Each of these classes can be subdivided into several subclasses, each of which have a different mode of action. All of the subclasses have either one or two main objectives in mind, i) the improvement of nutrient use efficiency and ii) increasing the plants ability to cope with environmental stress conditions (biotic and abiotic).

### 1. Introduction

The well-known theory of 'The law of minimum' by Justus von Liebig is still the fundamental principle upon which plant cultivation is built upon today. The law of minimum states that yield is proportional to the amount of the most limiting plant growth factor, whichever factor it may be.<sup>2</sup> From this, it may be inferred that if for example a deficient nutrient is supplied, yields may be improved to the point that some other growth factor becomes limiting. This can be visually described by the popular image of the leaking barrel as shown in Figure 1. One component, of all the complex plant growth factor interactions, is plant nutrition. This is done by the application of fertilizer. The word 'fertilizer' can be defined as any substance, natural or chemical, that is added to the soil or directly to plants to improve fertility or enhance plant growth and health.<sup>10</sup>



**Figure 1:** Law of minimum showing the different possible limiting factors on the yield potential.<sup>2</sup>

## 2. A short history of micronutrients – the birth of speciality fertilizers

The use of fertilizer has been common practice for thousands of years, but only recently, advances in the understanding of plant growth, gave rise to much more specialized fertilizers. In 1910 Agulhon reported field responses of several crops to B, and in 1914 Maze claimed from solution culture experiments that small amounts of B were essential for maize.<sup>4</sup> By 1923 there was strong evidence that, in addition to the macronutrients, five more elements (Cu, Fe, Mn, Zn and B) increased plant growth when present in trace amounts.<sup>5</sup> Today, 17 nutrients are recognized as essential for plant growth. Three main classes (based on the amount needed by plants) exist namely macro-, secondary- and microelements. Table 1 shows the nutrient classes.

**Table 1:** The 17 essential plant growth elements in the three different classes.<sup>5</sup>

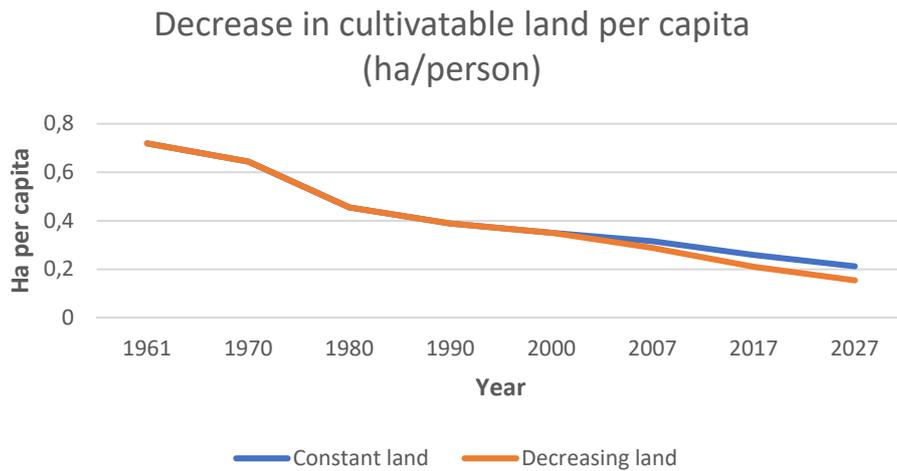
Macro elements	Secondary elements	Micro elements
Carbon (C)	Calcium (Ca)	Boron (B)
Oxygen (O)	Magnesium (Mg)	Copper (Cu)
Hydrogen (H)	Sulphur (S)	Cobalt (Co)
Nitrogen (N)		Iron (Fe)
Phosphorous (P)		Manganese (Mn)
Potassium (K)		Zinc (Zn)
		Molybdenum (Mo)
		Chlorine (Cl)

### **3. Speciality fertilizers – Essential or a nice to have?**

Diminishing arable agricultural land coupled with a fast growing world population has placed a sharp emphasis on the need for much more intensive agricultural practices. The FAO 2010 World Soil Resources Report isolated erosion hazard, aluminum toxicity, soil shallowness and hydromorphy as constraining between 13 – 16 per cent of global arable land area, which increased by 1.1 % per decade since the year 2000.<sup>6</sup> Irrigation, deforestation, desertification, terracing, land fill, urban encroachment and issues surrounding topology and land mass further constrain availability of arable land. According to the Global Land Assessment of Degradation published by the United Nations' Food and Agricultural Organization (FAO), nearly two billion hectares worldwide has been degraded since the 1950s.<sup>6</sup> It is projected that by 2050 the world will have a total of nine billion mouths to feed, which represents an increase of around 40 % on current levels. This will demand an additional billion tons of cereal and 200 million tons of meat to be produced annually by 2050.<sup>6</sup> To put this dilemma in a South African context:

Only a third of South Africa receives enough annual rain for crop production, and only one third of this rainfall area (approximately 12 % of the surface area of the country) has fertile soil. Furthermore, most of these areas are marginal for crop production, which means that only around 3 % of the total surface area is high potential cultivatable land.<sup>7</sup> Lower rainfall and high erosion rates is causing the cultivatable land to decrease even further. Coupled to this fact, is the estimation of population growth in South Africa, which is growing at an estimated rate of 2 % annually and is expected to reach 82 million by 2035.<sup>7</sup>

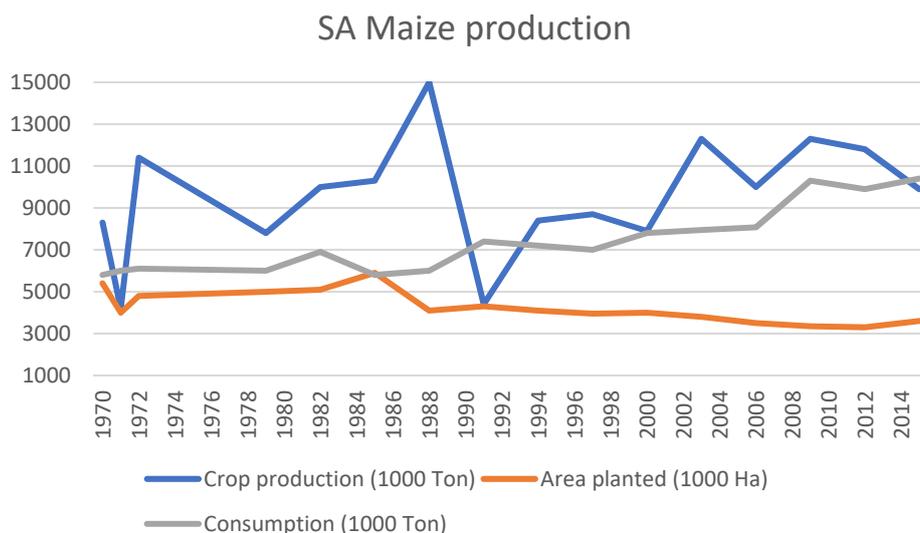
A study conducted in 2007, showed the alarming decrease in cultivated land per capita. The study stretched from 1961 to 2007 in  $\pm 10$  year intervals. Using the data collected, a graph showing the decrease can be plotted, which also shows extrapolated data for 2027 at a population growth rate of 2 % per annum, assuming the cultivatable land stayed constant from 2007.



**Figure 2:** Decline in cultivatable land per capita from 1961 to an extrapolated 2027 value. The figure shows the decline with and without diminishing cultivatable land.

#### 4. Adapt or perish

Looking at Figure 2, it is clear that all efforts must be made to use the available cultivatable land as efficiently as possible. Several agricultural practices can be used to improve the yield potential of a specific land area, which includes better cultivar-, fertilizer-, water use- and soil health management practices. During the last few decades, these management practices led by scientific research have helped increase crop yields per land area, substantially. Figure 3 shows the maize production (staple crop), area planted and consumption in South Africa as well as the area planted from 1970 to 2015.



**Figure 3:** Maize production in South Africa, area planted and consumption from 1970 to 2015. From statistics SA.

From Figure 3 it can be seen that the planted area has decreased significantly since 1970. The maize production has stayed relatively constant, which means that the yields per unit area has increased considerably. This can be attributed to the better management practices above. Furthermore, it can be seen that the consumption is at the highest it has ever been, higher than the average maize production over the last 40 years. We will have to find new innovative ways to increase our yields to meet the ever growing demands.

## **5. Improving yields with smarter speciality fertilizers**

A decrease in water resources, puts a sharp focus on better fertilizer technology. Fertilizer is not only important for direct plant nutrition purposes, but is also important for the condition and health of soils.

There are several types of fertilizers which can be classified according to their mode of action, application method and source/composition. Specialty fertilizers are applied to soil, seed and plants to improve the crop's physiological processes – its growth, blooming and maturity period. Speciality fertilizer is a fast growing market, with an estimated growth rate of 8.5 % per annum globally. The market is estimated to reach 24 billion USD by 2022.<sup>8</sup>

## **6. Speciality fertilizers classes**

Speciality fertilizer can be divided into 3 classes:

1. Nutrient speciality fertilizer
2. Biostimulants
3. Biological fertilizer/stimulants

This paper will discuss the most widely used speciality fertilizers available in the market.

### **6.1 Nutrient speciality fertilizers**

Nutrient speciality fertilizers are very versatile can either be applied via seed treatment, pre-plant or as foliar fertilizer. They can be divided into 3 subclasses.

- i) Water soluble, high purity macro- and secondary nutrient salts
- ii) Micronutrients (foliar, seed treatments, fertilizer coatings)
- iii) Inhibitors and slow/controlled release fertilizers

The methods of application, types/forms and special considerations when using the different nutrient speciality fertilizers will now be discussed.

### 6.1.1 Water soluble, high purity macro- secondary nutrients

These are high purity, water soluble salts of nutrients that are usually applied as a foliar spray or hydroponics at specific growth stages to supplement nutrient shortages that may occur. They can be in granular, liquid or powder form. Examples include mono ammonium phosphate (technical), calcium nitrate, magnesium sulphate, potassium nitrate etc.

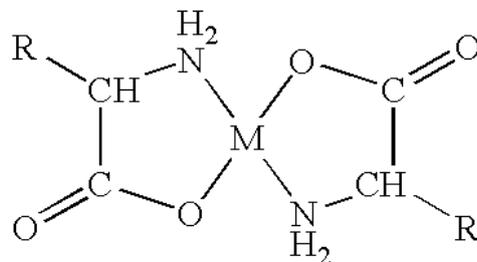
### 6.1.2 Micronutrients

Micronutrients in agriculture can be applied in many ways. These include foliar sprays, hydroponics, seed treatments, micronutrient granules blended into granular fertilizer as well as the practice of coating micronutrients onto the granular fertilizer. It is well known that in order for nutrients to be assimilated by a plant, it must be in water soluble form.

#### 6.1.2.1 Foliar micronutrients

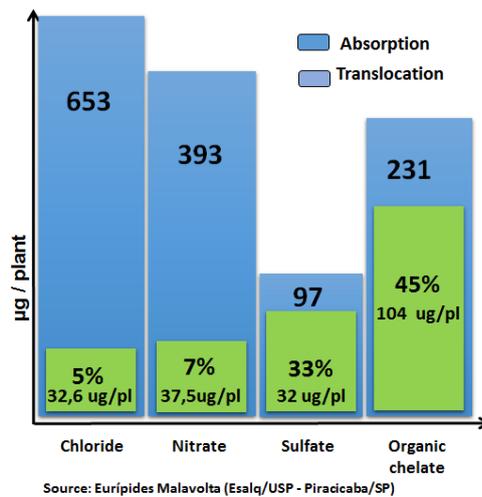
Most micronutrients, with the exception of boron and molybdenum, are transition metals. These include copper (Cu), iron (Fe), manganese, nickel (Ni) and zinc (Zn). They are taken up by plants in the divalent ( $M^{2+}$ ) form. The transition metals are very sensitive to pH change and easily form oxide or hydroxides, rendering them insoluble and not bio-available. Furthermore, these metal ions also react with ionic counter ions such as phosphate in the soil, forming insoluble, very stable metal phosphate compounds. For time constraint and financial reasons, micronutrients are also often co-applied with herbicides, fungicides and pesticides, which can also cause the formation of insoluble metal complexes, which decreases the efficacy of both the micronutrients and the other additives in the tank mixture.

To overcome these problems, these metals are protected with anionic compounds in a process called chelation. Many chelate types are available in the market, ranging from synthetic chelates such as EDTAA, to chelates with natural substances such as organic acids and amino acids. An example of a metal amino acid chelate is shown in Figure 4.



**Figure 4:** Example of a metal amino acid chelate, where M is a metal such as  $Cu^{2+}$ ,  $Fe^{2+}$ ,  $Mn^{2+}$ ,  $Ni^{2+}$  or  $Zn^{2+}$ .

Chelates are very pH stable, with synthetic chelates being the most stable but they are slow to degrade in the soil and offer metabolic value to plants. If formulated correctly, the organic chelates are stable enough for effective use, with the added advantage of being an energy/carbon source for the plant. The foliar uptake of nutrients is one important part, but the aspect which is even more critical is the ability of the nutrients to be translocated to other plants organs once taken up. These organic chelates not only exhibit excellent uptake ability by plants, but translocation within the plant is also very high, so the nutrient can move effectively to where it is needed. Figure 6 shows the difference between the uptake and translocation between organic chelates and chloride-, nitrate and sulphate metal salts.



**Figure 5:** The difference between the uptake and translocation between organic chelates and chloride-, nitrate and sulphate metal salts.

From Figure 5, it is clear to see that the effective movement of the chelate bound metals are much higher. Most of the salts are just taken up and remain in the leaf.

### 6.1.2.2 Nutrient seed treatments

Seed treatments are mostly used to supply the young seedling with micronutrients for its early growth period, when the roots are still developing. Micronutrients are immobile in most soils, which can result in early season deficiencies. This has been shown to result in stronger seedlings which can translate into higher yields. A polymer is often added into the seed nutrient mixture to ensure adequate adhesion onto the seed, together with a colorant for identification of treated seeds.



**Figure 6:** Improved root development of the maize plants from the nutrient treated seeds.

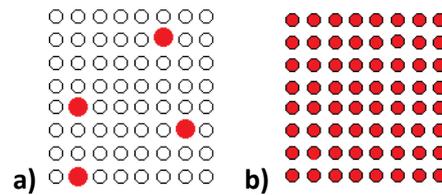
Common nutrients used in seed treatments include: The macronutrient phosphorous and the micronutrients manganese, molybdenum and zinc. The inherent salt index has to be low, to prevent osmotic stress the seed, which will result in a reduction of germination.

#### **6.1.2.3 Blended and coated micronutrients in bulk fertilizers**

Early supply of micronutrients to crops is important for early growth and establishment. There are two popular ways with which are applied at planting at the moment. Firstly, micronutrient granules can be blended into the macronutrient fertilizer at a given concentration. The second practice is coating of the micronutrients onto the fertilizer granule. The problem associated with the practice of granular fertilizer blending is the uneven spatial distribution over the planting area. A practical way to illustrate this is to use the addition of the micronutrient zinc to planting fertilizer as an example:

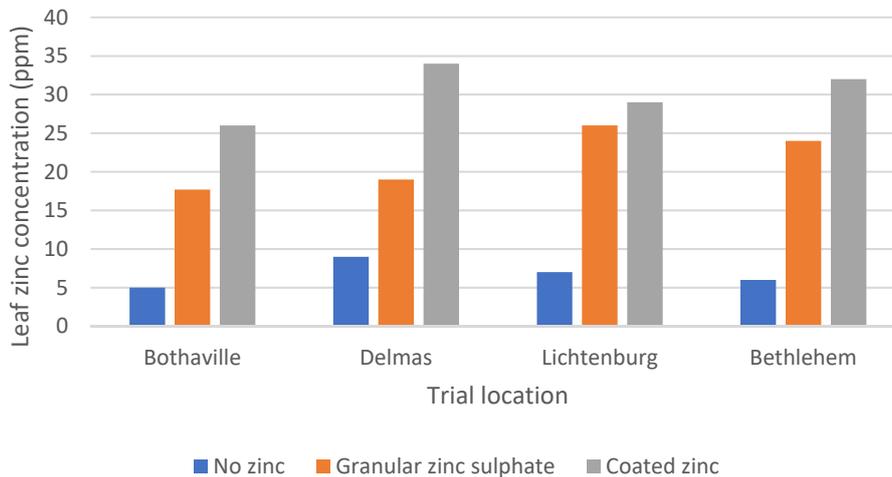
A blended granular fertilizer which is broadcast evenly at a rate of 200 kilogrammes per hectare equates to approximately 500 granules per  $m^2$  (this varies based on the particular blend characteristics). If 1250 g of zinc is needed per hectare to supply sufficient zinc to the crop, a typical blender would blend in zinc sulphate granules (containing 35% Zn) at a rate of 15 kg per ton of blended fertilizer. Using the bulk density of a common zinc sulphate granule (1.5, which is substantially higher than the macronutrient granules), it can be calculated that at a rate of 200 kg fertilizer blend per hectare, there will only be an average of 5 granules of zinc sulphate per  $1m^2$ . This means that there are only 5 zinc carrying entities in every  $m^2$ . The spatial distribution of these will also vary significantly, which may result in large parts of the  $m^2$  not receiving any zinc granules. Using the calculation, we see that only 1 in every 100 granules are zinc granules. Efficient coating ensures that every fertilizer granule is coated with zinc, making every granule a zinc carrying entity. This means that the zinc is

much more evenly distributed over every m<sup>2</sup>. If every granule is coated, there are now 500 zinc containing granules, which is 100 times more than in a granular blended zinc.



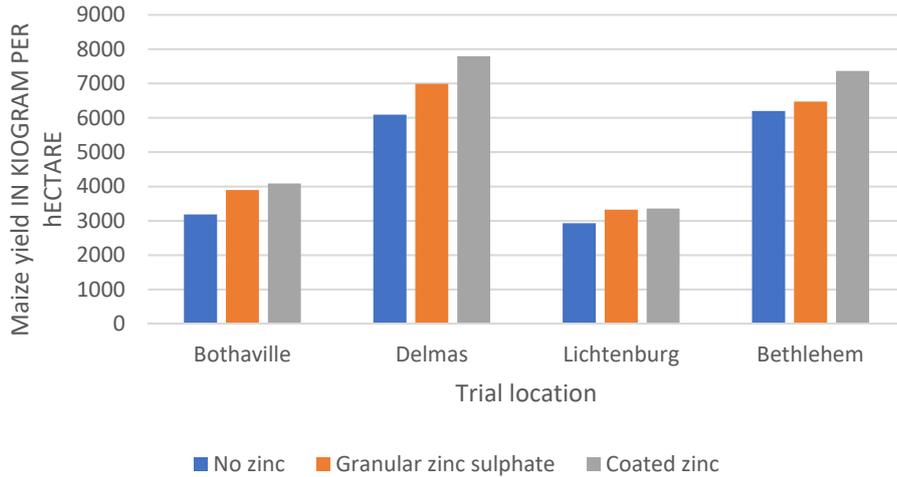
**Figure 7:** Bulk blend with blended a) zinc granules - Uneven spatial distribution and bulk blend with b) zinc coated granules.

In Figure 8, the results of leaf analysis on maize is shown for 4 trial locations, containing 5 statistical plots, for a no zinc (control) treatment, a granular zinc sulphate treatment as well as a coated zinc treatment, respectively. Eight leaf sample replicates were taken for each treatment and each location.



**Figure 8:** Zinc leaf analysis of maize at 4 different trial locations (2016/2017 season). Treatments differed only in zinc type. No zinc, granular zinc sulphate and coated zinc. The same zinc equivalent was used for the zinc sulphate and coated zinc treatments per hectare.

With the exception of the Lichtenburg trial, the zinc coating treatments produced statistically significantly higher leaf zinc concentrations than the granular zinc sulphate treatments. Both the zinc sulphate and zinc coating treatments were always significantly higher than the no zinc control treatment. The maize yields were also measured for the different zinc treatments and is shown in Figure 9.

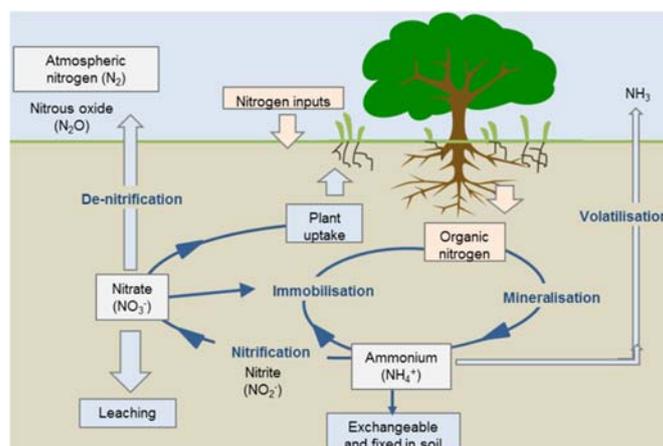


**Figure 9:** Average maize yields of the four trial locations for the different zinc treatments (2016/2017 season). Five statistical plots were planted for each treatment at each location.

From Figure 9, it can be seen that the zinc coated treatment resulted in the highest maize yields, followed by the zinc sulphate treatment and the no zinc treatment had the lowest yield results. In the Delmas and Bethlehem trial locations, the average yield increase of the zinc coated treatment was significantly higher than both the no zinc and zinc sulphate treatments. In the other two locations, an average yield increase for the zinc coating was also observed over the no zinc and zinc sulphate treatments, but it was not statistically significant.

### 6.1.3 Inhibitors and slow/controlled release fertilizers

During the crop season, however, nutrients can be lost to the groundwater, to the air and into the soil's organic matter as a result of biological and physical activity in the soil. These losses mean that farmers don't always fully benefit from the application of their fertilizers. An example is the losses of nitrogen as shown in Figure 10, which shows the nitrogen cycle.<sup>17</sup>



**Figure 10:** The nitrogen cycle.<sup>17</sup>

Major nitrogen losses from fertilizer inputs are caused by leaching and volatilization annually. Urea nitrogen is converted to ammonium in the soil by the soil enzyme urease. The dissolved ammonium volatilizes and ammonia gas is produced and lost to the atmosphere. Urease inhibitors slows down this process causing nitrogen to be available for longer in the soil.

For plant uptake, ammonium in the soil is oxidized to nitrites and finally nitrates, by a bacterial mediated process called nitrification. Two bacterial classes are involved, nitrosomonas and nitrobacter. Nitrates are very water soluble and mobile in the soil, which can cause high levels of nitrogen losses through leaching. A class of substances called nitrification inhibitors slows down this process of nitrification and maintains nitrogen levels in the soil.

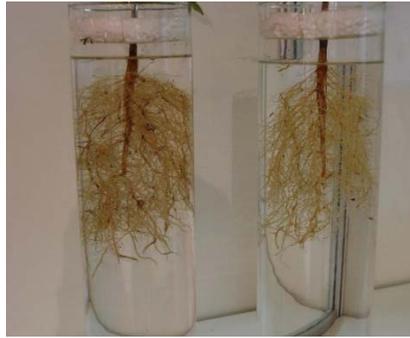
Whilst inhibitors delay nitrogen losses for up to 3 weeks, another class of fertilizers called slow- or controlled release fertilizers. They can keep fertilizer plant available for weeks and even months. These fertilizers are protected by a physical barrier, which controls the release of fertilizer of extended time periods. The physical barrier is usually in the form of a polymer coating. The polymers can be designed to release nutrients at a certain soil moisture or temperature. Some coatings are also degraded by soil microbes to provide a specific nutrient release curve.<sup>9</sup>

## **6.2 Biostimulants**

Biostimulants are defined as any substance or microorganism applied to seeds, plants or the soil with the aim to enhance nutrition efficiency, abiotic stress tolerance and/or crop quality traits, regardless of its nutrients content.<sup>9</sup> The biostimulant market has grown exponentially over the past few years with an estimated global market value of over 2 billion USD in 2018.<sup>8</sup> While there are a vast number of biostimulants available in the market, they can mainly be divided into 4 subclasses.

### **6.2.1 Seaweed extracts**

One of the most popular growth enhancing biostimulants in the market is seaweed extracts. They contain a range of complex carbohydrates, plant hormones (cytokinins and auxins), macro- and micronutrients, betaines (and other amino acids) and sterols. Seaweeds act on soils and on plants which means that they can be applied on soils, in hydroponic solutions or as foliar treatments. Apart from its growth stimulating effect, seaweed extracts contain high amounts of antioxidants which is effective in plant stress relief.<sup>12</sup> A lot of trial data of the use of seaweed extracts is available in literature.



**Figure 11:** The effect of seaweed treatment (left) and untreated (right) on root development.

### 6.2.2 Plant hormones

The use of synthetic plant hormones (also produced naturally in the plant) has also been shown to be very effective in stimulating plant growth and crop quality traits. There are 5 major classes of plant hormones and each of them are involved in controlling specific metabolic processes. Table 2 gives the 5 hormone classes, examples of each class as well as the function of each hormone class in plant development.

It is important to note that the various hormones have a powerful effect on plant growth and care should be taken when using plant hormone products. The use of such products should always be done in conjunction with a specialist.

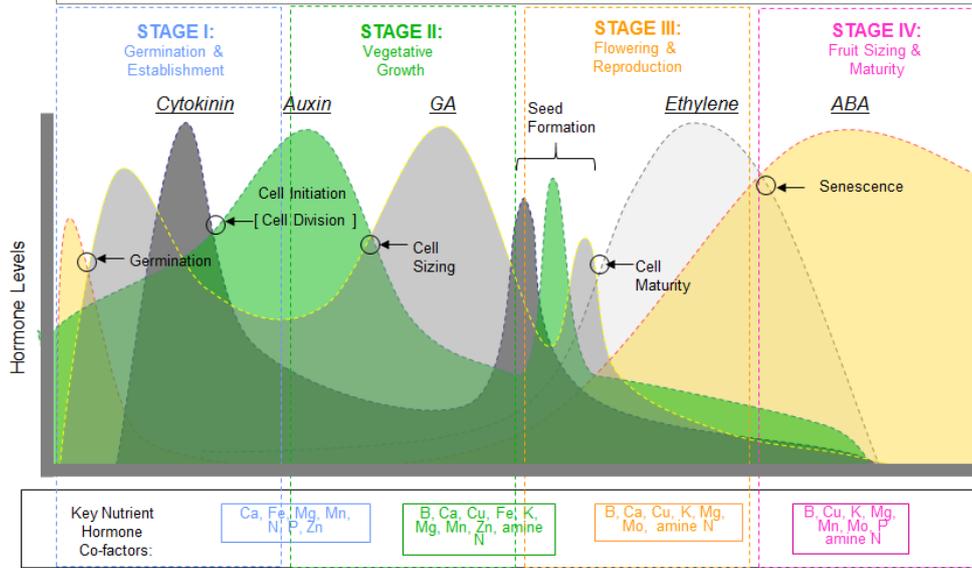
**Table 2:** The 5 major classes of plant hormones, examples of each and their respective plant functions.<sup>10</sup>

Hormone	Example	Important functions in plant
Auxin	Indole acetic acid (IAA); Naphthalene acetic acid (NAA); Indole butyric acid (IBA)	Stimulates cell elongation Stimulates cell division with cytokines Stimulates root growth Promotes stem elongation Inhibits growth of lateral buds (maintains apical dominance) Initiates flower formation
Cytokinin	Zeatin Kinetin 6-benzylaminopurine -(6BAP) diphenylurea	Stimulates photosynthesis Stimulates cell broadening Stimulates cell division with auxins

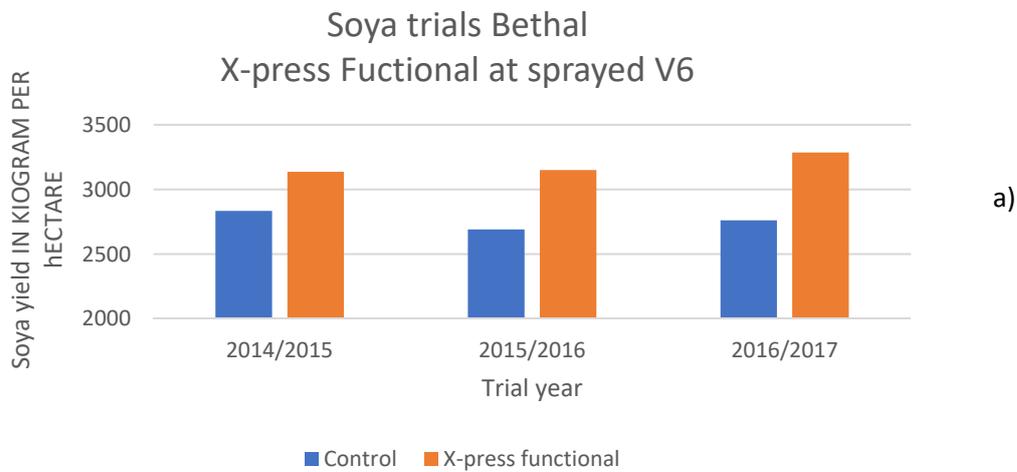
		Promotes stomatal opening Stimulates lateral bud development
Gibberellins	Various forms of Gibberellic acid	Stimulates shoot and cell elongation Delays senescence of leaves Stimulate root growth Stimulates seed germination Dormancy breaking
Abscisic acid	Abscisic acid (ABA)	Abscisic acid is a hormone involved in counteracting the effects of the 3 hormones mentioned above. Stimulates stomatal closure Involved in seed and bud dormancy
Ethylene	Ethylene (ET)	Stimulates flower and leaf senescence Leaf abscission in older leaves Stimulates fruit ripening Helps induce seed germination

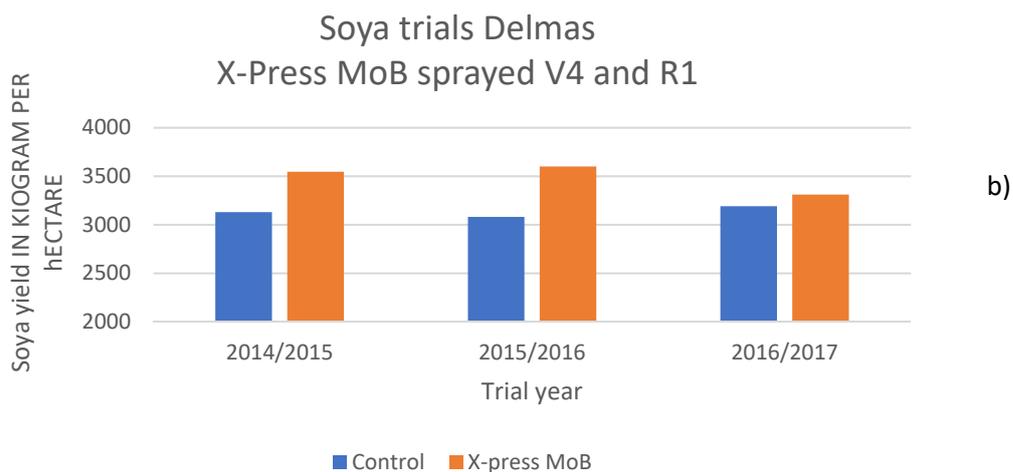
The concentration of these hormones fluctuate with varying stages of plant development, to elicit a specific metabolic response. Research have also suggested that these plant hormones work in synergy with plant specific plant nutrients at the specific growth stages. The hormone involvement and nutrient synergies are shown in Figure 12.

# Plant Hormone Balance & Cycles



**Figure 12:** The fluctuating hormone levels and nutrient synergies at different plant growth stages. Adapted from Stoller USA.





**Figure 13 a) and b):** The effect of two different hormone products containing complimentary nutrients on the average soya crop yield. The control treatments only contained the nutrients without the hormone compounds. Five Replicates were done per treatment.

### 6.2.3 Organic compounds

#### Humic and fulvic acids

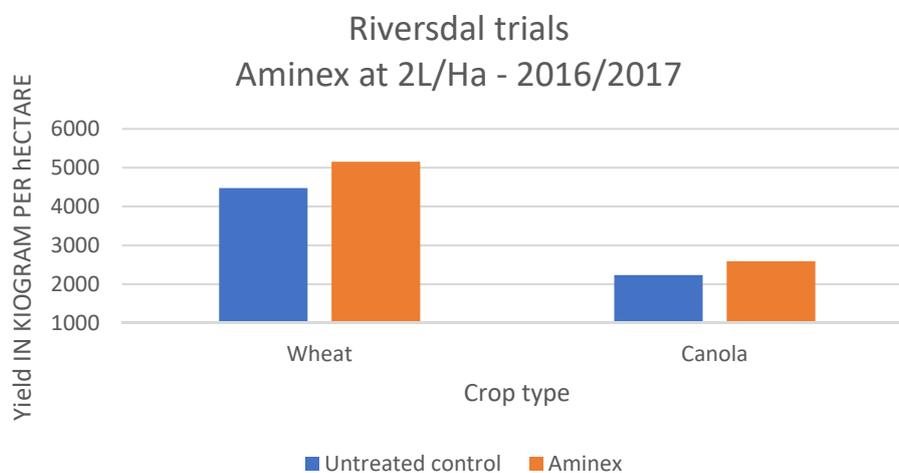
Humic substances are natural constituents of the soil organic matter, resulting from the decomposition of plant, animal and microbial residues, but also from the metabolic activity of soil microbes using these substrates. Humic acids are found in layers of sedimentation of soft brown coal called Leonardite. Leonardite is organic matter that has not yet reached the state of coal and differs from soft brown coal by its degree of oxidation. Humic substances improve soil fertility, acting on physical, physico-chemical, chemical and biological properties of the soil. Humic acids have been shown to retain nutrient ions thus preventing them from leaching. They also buffer plants from too high concentrations of fertilizer salts. Also, humic acids have been shown to increase germination rates and promote greater fibrous root growth.<sup>12</sup>

Fulvic acids, are humic substances known to be powerful organic electrolytes which help to dissolve minerals and metals. In other words, fulvic acids transform minerals so that they are readily available for absorption by plants. Fulvic acids work more in the plant than in the soil. They enhance nutrient, vitamins, coenzyme, auxin, and metabolism, which contribute significantly to plant growth and health. An indirect way in which fulvic acids help plants to withstand wilting is by increasing the amount of carbohydrates which results in the accumulation of soluble sugars in the cell. This increases the osmotic pressure on the cell walls and makes the plant better able to deal with drought stress. Lastly,

fulvic acids help to sensitize and enhance the permeability of the cell membrane which assist in the nutrient uptake.<sup>11</sup>

### Amino acids

Amino acid sprays can be very beneficial to plants. Studies have shown that amino acid supplementation improve photosynthesis by increasing the basal chlorophyll concentration, resulting in more available metabolic energy. Amino acids are also important in stomatal regulation, and foliar amino acid sprays have also been shown to support stomatal function. Amino acids help with the fertility of pollen, increase pollen germination and the length of the pollen tube, which improves fruit set. It strengthens cell walls for longer shelf life and helps improve the ripening stage of fruits, benefiting flavour and terpene production.<sup>12,13,14</sup> Amino acids are excellent chelating agents which is important in the uptake and transport of nutrients within the plant. Amino acids (especially betaine, proline and glycine) also have antioxidant capabilities, which means that they are valuable in mitigating environmental stress conditions.<sup>14</sup> Figure 15 below shows the results of an amino acid biostimulant treatment sprayed on both wheat and canola in the Riversdal area in 2016/2017 season. A statistically significant average yield increase was seen over the control in the wheat trial. Five replicates were done for each trial for both the wheat and canola trials.



**Figure 14:** The effect of an amino acid spray treatment on the yield response of wheat and canola in the Riversdal area. Application of the product was 2L/Ha. Wheat was sprayed at flag leaf stage, whilst canola was sprayed at the end of flowering.

### Salicylates

Salicylates are a class of organic compounds which cyclic structure resembles that of plant hormones. The most popular salicylate used as biostimulant today is salicylic acid. Salicylic acid (SA),

a plant hormone-like substance that plays an important role in induction of plant defence against a variety of biotic and abiotic stresses through morphological, physiological and biochemical mechanisms. It is often referred to as an eliciting compound, because it elicits a defence response by the plant. Plant elicitor compounds are chemical molecules that can either be naturally produced by a plant itself, or it can be an exogenously applied chemical compound that elicits certain responses by a plant. In most cases these compounds act as plant stress signals in response to pathogenic attack or unfavourable environmental conditions, which activates gene regulated resistance to a given stress. Two types of resistance have been identified in plants: Systemic acquired resistance (SAR) and induced systemic resistance (ISR). With SAR, the plant produces compounds such as salicylic acid that activates defence mechanisms once it comes in contact with a pathogen or experiences unfavourable environmental conditions. ISR is mostly an indirect effect, where a pathogen infected plant produces volatile signalling molecules such as jasmonic acid (JA) or ethylene, which in turn causes other parts of the plant and surrounding plants to activate their defence mechanisms to pathogenic attack. Exogenous application of salicylic acid can be sprayed foliarly to mimic stress conditions, which can be compared to immunisation in animals and humans, activating the immune system, to help fight off future infections.

### **Chitosan**

An organic biostimulant often used in agriculture is chitosan. Chitosan is a glucosamine biopolymer which is extracted from chitin in crustaceans (such as shrimps) or fungi. The extraction process is done by alkalizing the chitin with sodium hydroxide to create a more water soluble sodium salt. The physiological effect of chitosan is due to its ability to bind to specific receptors involved in defence gene activation, in a similar way as plant defence elicitors such as pathogens. Chitosan elicits the accumulation of phytoalexins, pathogen-related (PR) proteins and proteinase inhibitors, lignin synthesis, and callose formation, preparing the plant for the eventuality of pathogen attack.<sup>14</sup> Chitosan products can be applied as seed treatment or foliar spray.

#### **6.2.4 Inorganic compounds**

Although there are many inorganic compounds that have been identified as having biostimulant effects, two of the most powerful inorganic biostimulants are phosphites and silicon.

### **Phosphites**

Phosphites have received a lot of attention in the past few years because of its known ability to act as a systemic fungicide. The most popular source of phosphite used in agriculture is the potassium salt of phosphorous acid, potassium phosphite. More advanced products use a polymerized form of

potassium phosphite, for a more sustained and safer supply of phosphites. Research have also revealed that phosphites have biostimulant abilities, such as increased root development, disease resistance, increased yields and fruit quality. Until recently the biostimulant mechanism of phosphites were poorly understood, but new evidence suggests that it stimulates genes for natural cis zeatin (cZ) type cytokinins production, which increases root growth and thus the uptake of water and nutrients.<sup>15</sup>

### **Silicon**

Although silicon is not regarded as an essential nutrient, it has some powerful biostimulant properties. Silicon is taken up by plant in the form of monomeric silicic acid ( $H_4SiO_4$ ). At a pH lower than 10, polymerisation of dissolved silicon occurs and polymerised silica forms. It is thus important to use a silicon source that has been stabilized, to be stable at normal water pH's used for cultivation. Silicon has been shown to alleviate abiotic stresses in higher plants through silica deposition inside the plant tissues which provides mechanical strength and erectness to leaves and modulates nutrient and water mobility inside the plants, stimulation of antioxidant systems in plants, complexation or co-precipitation of toxic metals with Si both in plant tissues and in soil, modulation of gene expression and signalling through phytohormones.<sup>16</sup>

## **6.3 Biological fertilizer/stimulants**

Biological fertilizers/stimulants can be of bacterial or fungal origins. Although some foliar products exist, most products available in the market are either applied directly to the soil or as seed treatments. Both bacterial and fungal products act upon plant growth in a mutualistic symbiotic way, with a varied mode of action. They improve plant growth by improving nutrient availability and uptake (biofertilization), producing compounds that stimulate growth and disease resistance, control of pathogenic organisms and pests as well as improving soil structure.

### **6.3.1 Beneficial bacteria**

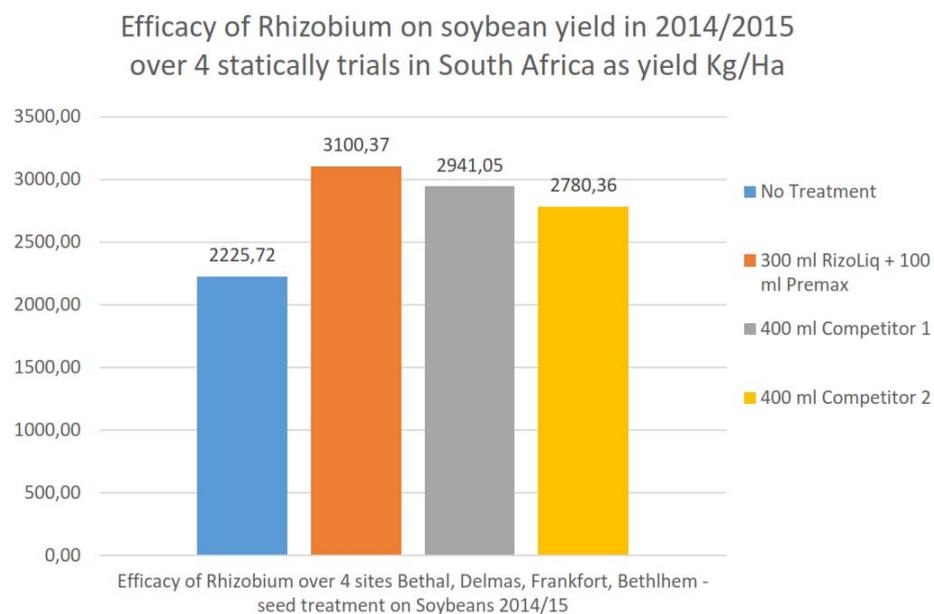
The most widely used biological organism in agriculture is nitrogen fixing rhizobium bacteria. These bacteria are widely applied as seed treatment or in furrow to help nodulation in legume crops. One of the most efficient nodulating rhizobium species in soybean cultivation is *Bradyrhizobium japonicum*. *Bradyrhizobium japonicum* is capable of forming a mutualistic relationship with soybean roots. During this mutualistic relationship the rhizobia receive carbohydrates and protection from the plant while the plant receives nitrogen in an available form from the bacteria. For the interaction to take place signalling from both parties are necessary. Flavonoids produced by the plant roots activate Nod genes in the rhizobia which in turn prepares the plant for invasion by bacteria and the formation of root nodules. The bacteria in these structures can convert atmospheric nitrogen to ammonia, supplying

the plant with enough nitrogen required for growth. Figure 15 shows the morphology of a healthy nitrogen fixing soybean nodule.



**Figure 15:** morphology of a healthy nitrogen fixing soybean nodule.

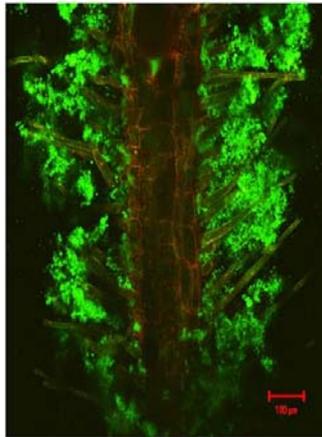
Although these nodulating bacteria is naturally present in soils, the practice of inoculation using for example *Bradyrhizobium japonicum* results in better nodulation, higher nitrogen fixation and finally higher yields. Different products are available on the market and the efficacy of the bacteria is usually correlated with the amount of viable colony forming units (cfu). A good product usually contains more than  $5 \times 10^9$  cfu at date of expiry. Figure 16 shows the effect of different inoculation products on the average soybean yield over the control with no inoculation, over 4 trial locations in 2014/2015.



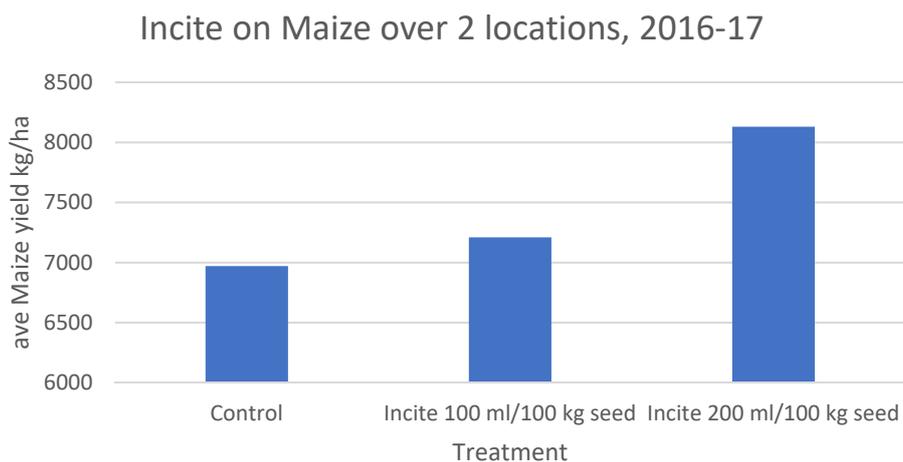
**Figure 16:** The effect of different inoculation products on the average soybean yield over the control with no inoculation, over 4 trial locations in 2014/2015.

Another example of beneficial bacteria is members of the genus *Bacillus*. They are termed plant growth-promoting rhizobacteria (PGPR) and are capable of effectively colonizing plant roots (Figure

17) and in the process exert beneficial effects on plant growth and development. Lipopeptides produced by *Bacillus* make these members highly effective plant root colonisers and improves their persistence in the root environment. Plant health is improved through three mechanisms: i) suppression of plant pathogens, ii) promotion of plant nutrition and growth, iii) promotion of plant defences. The production of various hormones by *Bacillus* (e.g. auxin, gibberellins and cytokines) can result in plant growth promotion.<sup>18,19</sup> Furthermore, phytases produced by some *Bacillus* strains exert biofertilization effects by solubilising phosphates as well as releasing nutritionally important minerals (e.g.  $Zn^{2+}$ ,  $Fe^{2+}$ ,  $Ca^{2+}$ ) from chelate-forming phytate. Several *Bacillus* strains have shown to induce plant resistance pathways.



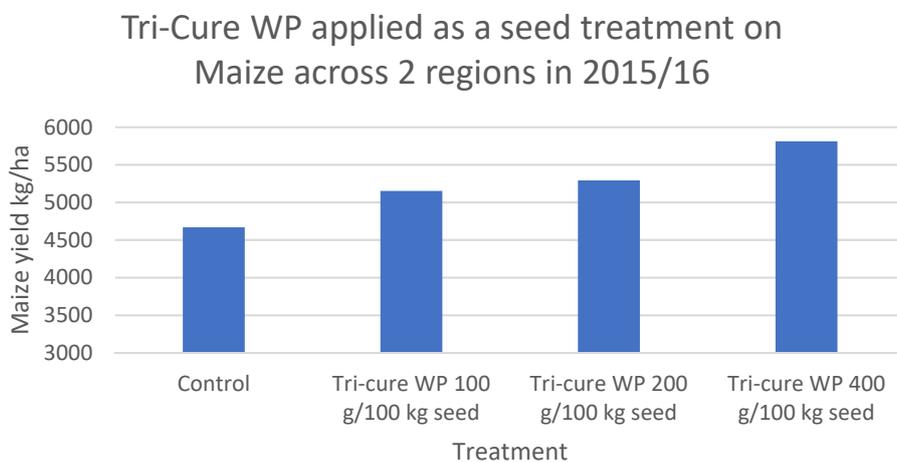
**Figure 17:** Microscope photo showing *Bacillus subtilis* (green) biofilms on an Arabidopsis root surface.  
Credit: University of Delaware/Thimmaraju Rudrappa



**Figure 18:** Average maize yield over two trial locations of with untreated and treated maize seeds. Incite is a *Bacillus methylotrophicus* specific *Bacillus* specie.

### 6.3.2 Beneficial fungi

The most common beneficial fungi used in agriculture is *Trichoderma*. Different species and strains are available which differ in terms of their ability to colonize the rhizosphere around the roots as well their mode of action on the plant. A very efficient strain of *Trichoderma* is *Trichoderma harzianum*. *Trichoderma harzianum*, is a soil borne, opportunistic plant symbiont, which forms beneficial relationships with a variety of plant species. It can easily adapt and survive in different soil types, is able to form a physical bond with the root system of its host plant and establish itself in the rhizosphere. Plant growth and root development is stimulated in the presence of *T. harzianum* through several mechanisms: (i) production of plant hormones (e.g. auxin), (ii) production of secondary metabolites and (iii) solubilisation of essential plant nutrients.<sup>20</sup> The secondary metabolite, harzianic acid, function as a plant growth promoter and solubilizes iron that would otherwise be unavailable to the plant. Furthermore, *Gliotoxin* produced by *Trichoderma harzianum* has a structure similar to the plant growth hormone gibberellic acid. Research has shown that the same receptor space used by gibberellic acid can also be occupied by gliotoxin. Gliotoxin was also shown to elicit similar physiological responses in bean plants as observed by gibberellic acid.<sup>21</sup> A range of secondary metabolites produced by *Trichoderma* (e.g. cellulase, xylanase) are involved in triggering induced systemic resistance in plants.<sup>20</sup>



**Figure 19:** Average maize yield over two trial locations of with untreated and treated maize seeds. Tri-cure WP is a *Trichoderma harzianum* fungal specie.

#### References:

1. C.J. Brand, (1945), Some Fertilizer History Connected with World War I, *Agricultural History*, 19 (2): 104–113.

2. T.I. Williams, T. Kingston Derry (1982), A short history of twentieth-century technology c. 1900-c, 1950, Oxford University Press. pp. 134–135.
3. H.D. Chapman, (1966), Diagnostic Criteria for Plants and Soils, Division of Agricultural Sciences, University of California, Riverside.
4. C.M. Donald, (1975), Trace elements in Australian crop and pasture production, 1924–1974, in Trace Elements in Soil–Plant–Animal Systems, eds. D.J.D. Nicholas and A.R. Egan, 7–37, Academic Press: Sydney.
5. H. Marschner, (1995), Mineral Nutrition of Higher Plants, 2nd ed., Academic Press: New York.
6. P. Campbell (2011), FDI Researcher, The Future Prospects for Global Arable Land, Global Food and Water Crises Research Programme.
7. M. du Plessis (2014), Agriculture: Facts and Trends, South Africa, a WWF-SA report.
8. Reuters market report, (June 2017) Specialty Fertilizers Market Size, Share, Report, Analysis, Trends & Forecast to 2022.
9. D. Abalos, S. Jeffery, A. Sanz-Cobenaa, G. Guardiaa, A. Vallejo, Meta-analysis of the effect of urease and nitrification inhibitors on crop productivity and nitrogen use efficiency, *Agriculture, Ecosystems and Environment* 189 (2014) 136–144.
10. EU fertilizer legislation board, Hamburg Germany, 2017.
11. H. Heldt, B. Piechulla, in *Plant Biochemistry* 4th Ed., 2011.
12. H.Y. Suh, K.S. Yoo, & S.G. Suh, Effect of foliar application of fulvic acid on plant growth and fruit quality of tomato (*Lycopersicon esculentum* L.), *Hortic. Environ. Biotechnol.* (2014) 55: 455.
13. I.R. Marhoon, M.K. Abbas, Effect of Foliar Application of Seaweed Extract and Amino Acids on Some Vegetative and Anatomical Characters of Two Sweet Pepper (*Capsicum Annuum* L.) Cultivars, *International Journal of Research Studies in Agricultural Sciences (IJRSAS)* Volume 1, Issue 1, May 2015, PP 35-44.
14. P. du Jardin, Plant biostimulants: Definition, concept, main categories and regulation, *Scientia Horticulturae* 196 (2015) 3–14.
15. Investigating the role of phosphite in plant development Lead Research Organisation: University of Nottingham Department Name: Sch of Biosciences [personal communication, 2018].
16. D. Savvas, Biostimulant activity of silicon in horticulture, *Scientia Horticulturae*, 2015, 196, 66-81.
17. A.N. Gorban, L.I. Pokidyseva, E.V. Smirnova, T.A. Tyukina, Law of the Minimum Paradoxes, *Bull Math Biol.* 73(9) (2011), 2013-2044.

18. D.K. Choudhary, and B.N. Johri, 2009. Interactions of *Bacillus* spp. and plants – With special reference to induced systemic resistance (ISR). *Microbiological Research*, 164: 493-513.
19. A. Perez-Garcia, D. Romero, A. de Vicente, 2011. Plant protection and growth stimulation by microorganisms: biotechnological applications of Bacilli in agriculture. *Current opinion in Biotechnology*, 22: 187-193.
20. F. Vinale, G. Manganiello, M. Nigro, P. Mazzei, A. Piccolo, A. Pascale, M. Ruocco, R. Marra, N. Lombardi, S. Lanzuise, R. Varlese, P. Cavallo, M. Lorito, S.L. Woo, 2014. A novel fungal metabolite with beneficial properties for agricultural applications. *Molecules*, 19: 9760-9772.
21. J. Bezuidenhout, L van Rensburg, P.J. van Rensburg, 2012. Molecular similarity between gibberellic acid and *gliotoxin*: Unravelling the mechanism of action for plant growth promotion by *Trichoderma harzianum*. *Journal of Agricultural Science and Technology*, 2(6B): 703.