

Basic Fertilizer Chemistry

Introduction

This publication contains basic chemistry information for understanding plant nutrients from an atomic viewpoint. This chemical information focuses on the elements that are required by plants. A fertilizer salesperson must supply these elements (in the form of compounds) to plants in an available and usable form. Therefore, it is important to fully understand the makeup and forms of these elements.

Chemistry - Understanding the Basics

This section focuses on the **essential elements** that make up plants. Essential elements are those elements that plants cannot properly grow, reproduce and function without. These elements are found in soils, air and fertilizers and are referred to as nutrients. Nutrients (plant food) are divided into two basic groups:

- 1) **Macronutrients** - “Macro” means large. These nutrients are required by plants in large amounts when compared to micronutrients. Macronutrients are also further divided into two classes; PRIMARY nutrients (N, P, K) and SECONDARY nutrients (Ca, Mg, S)
- 2) **Micronutrients** - “Micro” means small. These nutrients are required by plants in small amounts. Although they are required in small amounts, they perform very important functions in plants and are often overlooked becoming the most limiting factor of plant yield and quality. They are B, Cl, Cu, Fe, Mn, Mo & Zn.

As you noticed we used the abbreviated form of listing the essential elements. These abbreviations are called atomic symbols, as you probably know, N = Nitrogen. Be sure that you know the full name of each of the atomic symbols. There is a table on the very last page of this write-up that you should be referring to throughout, which is a complete listing of all the elements found in nature and listed in an orderly fashion called the PERIODIC TABLE OF ELEMENTS. On the second last page of this manual you will find a table that lists all the elements found in plants. Through this manual we will refer only to the elements in relation to the makeup of plants.

The individual forms of nutrients required by plants are called elements. To fully understand the function of these nutrients and the chemical forms of these nutrients in plants and soils, you must first understand the basics.

ATOM – If you take a piece of copper (penny or wire) and cut this piece into smaller and smaller pieces, the smallest possible piece of copper you could have would be one atom of copper. If you cut it further, it would no longer be copper.

To understand why you cannot buy pure N (nitrogen) you must first learn about the atomic structure (the makeup of the smallest possible “piece” of nitrogen). Once you fully comprehend this structure, you will see why they must combine with other elements to remain **stable** and to be in a usable form. Example, N is available as ammonium (NH₄), nitrate (NO₃) and urea (CH₄N₂O).

ATOMIC STRUCTURE – the makeup of an atom. This smallest form of each element (an atom) is made up of three basic particles: **neutrons, protons** and **electrons**. It is very important to get a “picture” of this makeup in your mind to be able to fully understand the function of plant nutrients in both soils and plants.

Neutrons – These particles are found in the center of the atom (**nucleus**). They are neutral in charge. They are the same size as protons. Each neutron is given a “weight” of ONE unit.

Protons – These particles are found in the nucleus of an atom. They have a positive charge (+). They are the same size as neutrons. Each proton is given a “weight” of ONE unit.

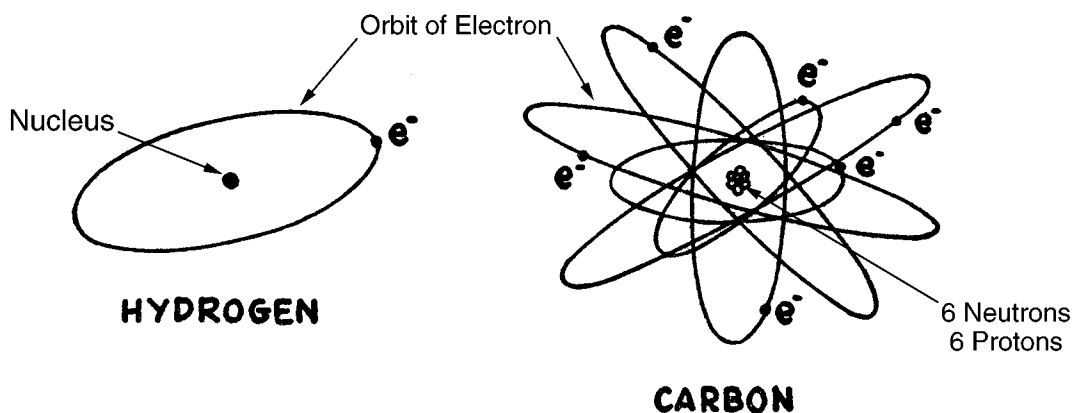
Electrons – These particles are found spinning around the nucleus of an atom. They are negative in charge (-). They are about 1,848 times “lighter” than the weight of a neutron or proton. Therefore they are considered to have a “weight” of ZERO.

Atomic Structure			
Particle	Location	Charge	Weight
Neutron	Center (nucleus)	0 (neutral)	1
Proton	Center (nucleus)	+1 (positive)	1
Electron	Orbit around center	-1 (negative)	0

Before we utilize an atom that applies to agriculture, you must first learn how to comprehend the terms **atomic number** and **atomic weight**. There are three points you need to remember to understand the chemistry and function of these elements:

1. In order for an atom to be neutral, the number of electrons must equal the number of protons. Remember, protons are positive (+) and electrons are negative (-). If you have the same number of each they will be neutralized.
2. The atomic number of each element is equal to its number of electrons and its number of protons. Look at the periodic table and you will find that carbon (the second most abundant element found in plants) has an atomic number of 6, therefore it has 6 protons and 6 electrons when it is in a neutral state.
3. The atomic weight of each element is equal to the number of protons PLUS the number of neutrons. In the case of carbon, the atomic weight would be 12.

If you have been looking at the periodic table at carbon (C) and other elements, you will have noticed that the atomic weight of carbon is shown as 12.011. Hydrogen, which has an atomic number of one, should have an atomic weight of two, right? Atomic number equals number of protons, which equals number of electrons, in case of hydrogen (H) this number is one. We also know that each element contains electrons, protons & neutrons. According to the rule above, the atomic weight equals the protons plus neutrons, which should be 2. Yet the periodic table shows that the atomic weight is only 1.0079. Why is this? Let us first look at a “picture” of hydrogen and carbon atom to help you further understand what you have learned to this point.



Before we can explain why the atomic weight of hydrogen is listed on the periodic table as only 1.0079, you have to learn two more important characteristics of the atom and its structure; Distribution of Electrons and Isotopes.

DISTRIBUTION OF ELECTRONS – As the diagram above illustrates, carbon has 6 neutrons and 6 protons in its center (nucleus) and orbiting around the nucleus you have 6 electrons. With hydrogen and carbon it is quite easy to visualize in your mind a picture with orbiting electrons with some order to it. However, try to draw up a more complex atom such as molybdenum (Mo). It has an atomic number of 42; therefore it would have 42 orbiting electrons with 42 protons and 42 neutrons in the center. This could be quite a confusing picture, couldn't it?

These electrons (negatively charged particles “-”) are distributed in a very orderly fashion and understanding this order is very critical to understanding how nutrients in agriculture are found in certain combinations. The electrons orbit in orderly orbits around the nucleus called “SHELLS”. Each of these shells is capable of containing a certain number of electrons. The closer the shell, the smaller the circle and therefore the less the “room” for electrons, right? Letters designate the shells, the first is “K”, the second is “L” and following as M, N, O & P. Before this can make any sense to you in drawing a picture of an atom, there are some basic “rules” to follow in how the electrons are distributed among the various shells:

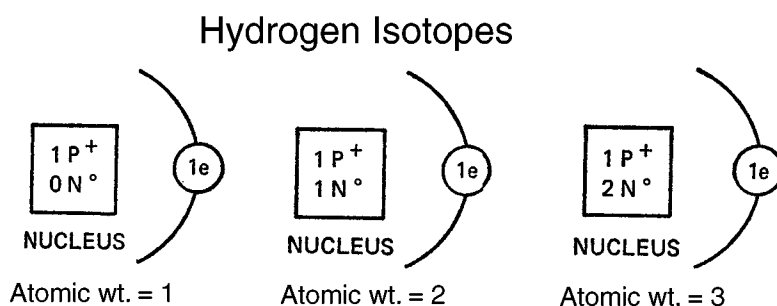
1. The first shell (K) holds only a maximum of 2 electrons, the second (L) holds a maximum of 8 electrons, the third (M) 18 electrons and the fourth (N) hold a maximum of 32 electrons.
2. In the first 18 elements of the periodic table (H to Ar) the shells are filled in order until they are full and then the next shell is started. (This will make more sense if you look at the table on the following page show the electron distribution of essential agricultural elements)
3. In the higher number atoms (Mo included) there can be 2 or 3 unfilled shells.
4. Up to 8 electrons temporarily fill each of the shells beyond the “M” shell and a new shell must be started before more electrons can be fitted into the temporarily filled shell. (Again the table will illustrate this better.)
5. There are never more than 8 electrons in the OUTERMOST shell.

As we stated, we are going to keep this manual related to agriculture. Therefore we have only listed the number of electrons in each shell of only the nutrients that relate to agriculture.

Distribution of Electrons							
Atomic			# of Electrons in Shells				
Number	Element	Abbr.	K	L	M	N	O
1	Hydrogen	H	1				
5	Boron	B	2	3			
6	Carbon	C	2	4			
7	Nitrogen	N	2	5			
8	Oxygen	O	2	6			
11	Sodium	Na	2	8	1		
12	Magnesium	Mg	2	8	2		
13	Aluminum	Al	2	8	3		
14	Silicon	Si	2	8	4		
15	Phosphorus	P	2	8	5		
16	Sulfur	S	2	8	6		
17	Chlorine	Cl	2	8	7		
19	Potassium	K	2	8	8	1	
20	Calcium	Ca	2	8	8	2	
25	Manganese	Mn	2	8	13	2	
26	Iron	Fe	2	8	14	2	
29	Copper	Cu	2	8	18	1	
30	Zinc	Zn	2	8	18	2	
42	Molybdenum	Mo	2	8	18	13	1

By now, you may be wondering what this has to do with agriculture but please stick with it! From the table above you are going to see why nutrients are referred to as cations (K^+ , Ca^{++}) or anions (P^{3-} , Cl^-). First, we will look at ISOTOPES and then a “picture” of some atoms.

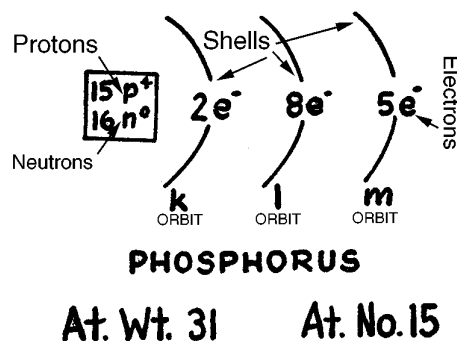
ISOTOPES – In nature not all elements are found in their simple form with equal amounts of neutrons and protons. As the diagram below illustrates, there are 3 types of hydrogen (H) arrangements known. The first contains only 1 proton (P+), 0 neutrons and 1 electron (e-), therefore the number of protons (1) plus the neutrons (0) equals an atomic weight of ONE. In the second there are 1 proton + 1 neutron = Atomic weight of TWO. There is also a form of hydrogen that contains 1 proton + 2 neutrons = Atomic weight of THREE. Now notice that the number of electrons and protons do not change. They cannot, because if there were two electrons, or protons this element would be helium, not hydrogen! Therefore, atoms can have varying amounts of neutrons and still be the same atom, but just a different ISOTOPE of this atom.



Now let's get back to the periodic table and the atomic weights listed there. In nature there are various isotopes found of every element. In the case of chlorine (Cl) a sample of naturally occurring chlorine is put in a jar. If you could pick out each atom and count the number of protons and neutrons in the nucleus of each atom, you would find about 75% of them have 17 protons + 18 neutrons = atomic weight of 35. About 25% of the atoms would have 17 protons + 20 neutrons = atomic weight of 37. Therefore, the average atomic weight would be about 35.5.

FINALLY! The reason hydrogen should be a 2, but is shown, as a 1.0079 is that MOST of the isotopes of hydrogen found in nature have no NEUTRONS! Hydrogen (H) is usually listed as a H⁺, therefore it lost its electron and is now only a PROTON.

Now, back to agriculture. If you look at the periodic table, phosphorus (P) is shown having an atomic weight of 30.974, which for practical purposes are 31. Now we know that the atomic number of P is 15. This means that it has 15 electrons and 15 protons. How many neutrons would it have? Remember, neutrons + protons = atomic weight.



Elements that are in a free state, or uncombined with other elements, make up only a small fraction of matter found in nature. Most matter is made up of combinations of elements (**compounds**) or mixtures of compounds.

COMPOUND – A compound is a combination of various elements. We have already mentioned that nitrogen (N) is never found as free N. For example a combination of N used in agriculture is nitrate (NO₃). This is then a combination of one atom of nitrogen and three atoms of oxygen. But before you can completely understand a compound, we must first take what we have learned to this point and add to it.

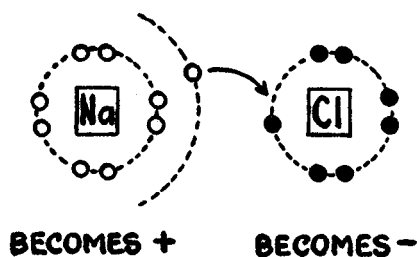
WHEN COMPOUNDS (two or more elements combining) ARE FORMED, ONLY THE ELECTRONS ARE INVOLVED IN THE REACTION. Furthermore, different combinations affect the electrons in the outermost shell.

Now let us examine the table on page 4 again. If you look at sodium (Na) it has an atomic number of 11. This means that it has 11 electrons. To fill its shells properly, it has 2 electrons in the first, 8 in the second and only 1 in the third shell. Yet, in chemistry you will notice that sodium is referred to as a **CATION** (Na⁺). Before we define this, let us also look at chlorine (Cl). You will notice that its outer shell consists of 7 electrons. In chemistry it is called and **ANION** (Cl⁻).

CATION – A cation is an element (or compound) with a positive charge. Now that you know more about the atoms and atomic structure, you can easily figure out what a cation is and why. Sodium has an atomic number of 11. Therefore, you know that it has 11 protons. Protons are positive and electrons are negative. Now, when the sodium loses an electron to make a stable outershell, it only has 10 electrons left. Now simply add up the charges: 11 protons (+ charge) minus 10 electrons (- charge) equals a positive charge of PLUS ONE (Na⁺ or Na¹⁺)

ANION – An anion is an element (or compound) with a negative charge. Let us go to our chlorine example. Its atomic number is 17, which is 17 protons (17 + charges). If it takes on an electron in its outer shell to make it a stable 8, it would gain an electron. Now it has 18 electrons (18 - charges). Therefore it has a net negative charge of MINUS ONE (Cl⁻).

But if Na gives up an electron and Cl gets one, what happens. The diagram below illustrates what happens:



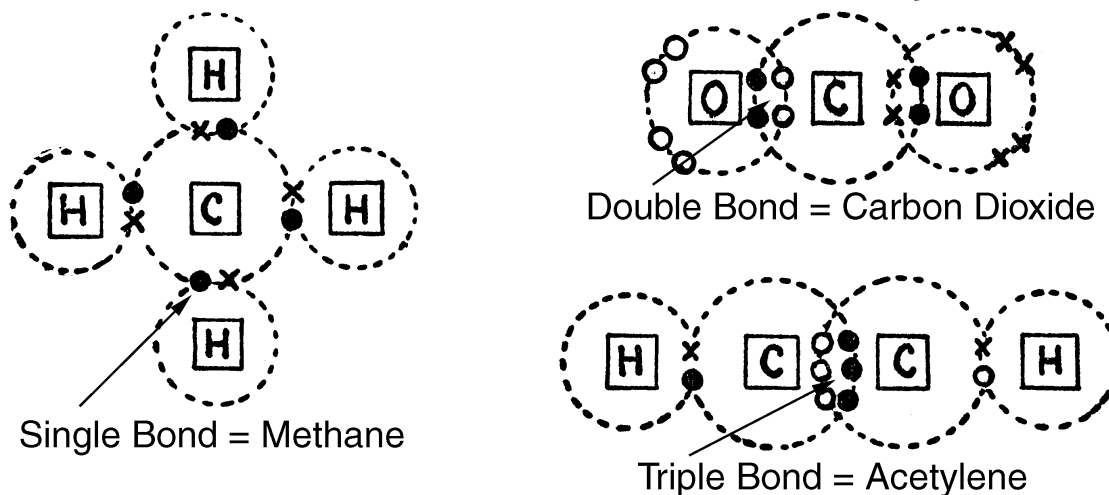
Now you have formed your first compound, table salt! The tendency of elements to form compounds because of a shift of electronic structure is known as **VALANCE**. The term valance is used to indicate two different things:

1. Valance Mechanism – This is the manner in which elements attain a **STABLE** electron distribution. (Na loses an electron, Cl gains an electron)
2. Valance Number – This is the number of electrons involved in the forming of a compound. (Examples: Na^+ , Ca^{2+} , Al^{3+} , Fe^{2+} , Fe^{3+} , N^3 , O^{2-} or Cl^- .)

To better understand the terms **CATION** and **ANION** we can use the formation of sodium and chlorine compounds to help. The sodium element as lost an electron. It becomes like the inert element number 10 (neon). It cannot become neon because it has 11 protons which is still sodium. But yet we cannot call it a true sodium atom because it no longer has 11 electrons. Now it has become an electrically charged particle called an **ION**. On the other end of the scale, the chlorine as gained an electron, which makes it electrically like argon. But it still has 17 protons so it is still chlorine, but it is now also an **ION** of chlorine called **CHLORIDE**. In both cation and anion you can now see were the “ion” comes from. “CAT” means “down” (the sodium is “down” one electron) and “AN” means “up” (the chlorine is “up” one electron).

ELECTROVALENCE – The first valance mechanism. This term relates to the process of forming a compound through the **transfer of electrons**. Mixing chlorine (Cl) with sodium (Na) results in transferring the electron from the Na to the Cl and forming a compound called sodium chloride, or table salt. Compounds formed by transferring electrons are still **IONS**, but are **NOT** molecules. A tablespoon of salt is not called a spoon of molecules, but a spoon of **IONIC AGGLOMERATES**.

COVALENCE – The second valance mechanism. This term relates to the process of forming a compound through the **sharing of electrons**. This will make a lot more sense to you if you first study the following pictures:



First go back one page and look at the NaCl again. Notice that an electron “jumps” **over** from the Na to the Cl (transfer of electron) and then both elements are now stable. In the covalence bonding, the elements **share** the same electrons. In the first one, you have a carbon atom, which are short 4 electrons in its outer ring to make a stable 8-electron configuration. So if you take 4 hydrogen atoms and run them by, their only electron wants to stabilize and “jump” **into** the carbon orbit. We used methane (CH₄) to show you this single bond example, because it is the main compound in natural gas that is used to make ammonia (NH₃), which is the base of almost all the nitrogen fertilizer you sell. Notice that in carbon dioxide (CO₂), the oxygen that has 2 extra electrons to share hooks up on each side. Carbon has TWO double bonds with oxygen to form this common gas that you exhale every time you breathe out.

To summarize this important topic of VALANCE MECHANISMS, look at the following table:

Valance Mechanisms		
Mechanism:	Electrovalence	Covalence
<i>Process:</i>	Complete transfer of electrons	Sharing of pairs of electrons
<i>Via:</i>	Formation of IONS	Interpenetrating of atoms
<i>Product:</i>	IONIC Agglomerates	Into MOLECULES

Before we can begin taking what we have learned to this point and begin making some agricultural applications of this chemistry, we must cover one more very important group of IONS (look back to fully comprehend an ion versus a molecule).

RADICALS – These are “clusters” of elements that behave as if they were a single element. They will be quite difficult to fully explain here because they do not have a definite structure by themselves, until they form a compound with another element.

However, because they are utilized in the formation of fertilizers and used by plants in free and combined forms, they are very important to understand.

This table lists common radical ions used in fertility:

Important RADICALS	
Valance Number of +1 Ammonium (NH ₄ ⁺)	Valance Number of -2 Carbonate (CO ₃ ²⁻)
Valance Number of -2 Bicarbonate (HCO ₃ ⁻) Hydroxide (OH ⁻) Nitrate (NO ₃ ⁻) Nitrite (NO ₂ ⁻)	Sulfate (SO ₄ ²⁻) Sulfite (SO ₃ ²⁻)
	Valance Number of -3 Phosphate (PO ₄ ³⁻)

In the following pages, we will focus on the forms of fertilizers commonly used in the industry. Understanding basic chemistry is an important precursor to further understanding the function and availability of nutrients in soil and foliar applications.

Fertilizer Chemistry

Now that we have a basic understanding of the chemistry, we will begin using more symbols in representing the information. The following table is modified from P.R. Stout, 1961, in *Proceedings of the 9th Annual California Fertilizer Conference*, pp 21-23. The interesting column is the last column, “Relative Number of Atoms Compared to Molybdenum”.

Element	Symbol	Form Available To Plants	Concentration in (ppm) in dry tissue	Relative # of Atoms compared to Mo
Molybdenum	Mo	MoO ₄ ⁻	0.1	1
Copper	Cu	Cu ⁺ , Cu ²⁺	6	100
Zinc	Zn	Zn ²⁺	20	300
Manganese	Mn	Mn ²⁺	50	1,000
Boron	B	H ₃ BO ₃	20	2,000
Iron	Fe	Fe ³⁺ , Fe ²⁺	100	2,000
Chlorine	Cl	Cl ⁻	100	3,000
Sulfur	S	SO ₄ ²⁻	1,000	30,000
Phosphorus	P	H ₂ PO ₄ ⁻ , HPO ₄ ²⁻	2,000	60,000
Magnesium	Mg	Mg ²⁺	2,000	80,000
Calcium	Ca	Ca ²⁺	5,000	120,000
Potassium	K	K ⁺	10,000	250,000
Nitrogen	N	NO ₃ ⁻ , NH ₄ ⁺	15,000	1,000,000
Oxygen	O	O ₂ , H ₂ O	450,000	30,000,000
Carbon	C	CO ₂	450,000	35,000,000
Hydrogen	H	H ₂ O	60,000	60,000,000

ESSENTIAL ELEMENTS – There is a very important distinction to make between **pure science** and **real agriculture**. The scientific definition of an “essential element” is as follows (from Plant Physiology, 4th Edition, by Salisbury & Ross):

“There are two principal criteria by which an element can be judged essential or nonessential to any plant: First an element is essential if the plant cannot complete its life cycle (that is, form viable seeds) in the absence of that element. Second, an element is essential if it forms part of any molecule or constituent of the plant that is itself essential in the plant (for example, nitrogen in proteins and magnesium in chlorophyll). Either criteria are sufficient to demonstrate essentially, and most elements in our list of 17 have met both....”

Our list on the previous page shows 16 elements, the official list also shows Nickel (Ni) which is the latest to be considered essential.

In pure science, there is no doubt that only these elements are considered “essential” in a laboratory condition of growing plants. However, remember that in agriculture, we operate in a little different environment. Rather than just being concerned about reproduction of seed, we also have to try to keep these plants alive and growing to their optimum potential. Here are some more elements that may not be considered “essential” in science, but show some very important characteristics for particular plants that are “essential” for farmers to produce:

1. **SILICA** – In a publication dedicated to suppressing plant disease and insect pressure through regulating plant fertility, we will be demonstrating how silica is one of the most overlooked nutritional tools in agriculture today.
2. **CHROMIUM** – In literature and our own private research, we have found that Cr plays an important role in making iron more available in plants. In some plants it is possible to correct iron chlorosis problems by foliar applying Cr.
3. **COBALT** – In our own research and demonstrations, Co can be used to help plants correct growth problems associated with unintentional chemical damage (from 2-4 D, for example). Tell a grower who has these problems that Co is not “essential” to him.
4. **ALUMINUM** – Although the function of Al is not known, it is found in all plants. We do not recommend applying it, but good or bad, Al is still in plants.
5. **SODIUM** – Although not essential for plant growth, it can substitute for potassium. Some agriculturally important plants such as sugar beets will show positive growth responses to application of Na if grown in low Na soils.