Agriculture defined as the domestication of plants and animals is found to have originated around 10,000 years ago. Prior to this, human race relied on fishing, hunting and gathering food for nearly 2 million years of its existence. The origination of agriculture coincides with a period where lot of climatic and ecological fluctuations took place. It was also observed that during the same period the growth in population increased to around 0.1 percent per year. It is not very clear whether the growth in population was responsible for the spread of agriculture or agriculture was responsible for the growth in population.

Agriculture is the largest user of land and water in the world occupying almost 1/3rd of the land area. It forms an important section of a country’s economy since it provides food and is a means of livelihood for the poor people of a country. Growth in agriculture can help poor countries in reducing poverty, which in turn can help in the economic growth of a country. The global population is expected to increase at around 9.3 billion by 2050. This has created new concerns regarding the ability of feeding the world in a sustainable manner. The demand for food is estimated to rise by 50 percent due to the estimated 27 percent increase in global population and 83 percent growth in income for the period 2005-2030. The use of crops for the production of bio-fuel and for other industrial use is also on the rise. Thus, these demands are going to have a significant effect on the limited agricultural resources available. Over the past five decades agricultural produce has increased significantly, thus making food affordable to many poor people in spite of an increase in the population. Worldwide production of grains such as wheat, rice and maize has almost tripled since 1960, thus resulting in the reduction of food prices. Technological innovations and use of inexpensive fossil fuels
has made it possible to increase agricultural production [1]. Green Revolution has helped significantly to increase the agricultural productivity, but due to high usage of chemical fertilizers and pesticides there have been signs of environmental degradation. Use of unsustainable practices in agriculture around the world, has resulted into its natural resource base getting damaged. In many of the developing nations, the main problems facing agriculture are soil erosion, scarcity of water and loss of habitat due to use of land for grazing, cropping and deforestation [2].

To meet the growing demands of agriculture for food and other industrial use, it needs to be practiced in a sustainable manner without putting any constraint on the already scarce resources. Agricultural productivity needs to be increased without any further damage to the environment through proper management of the available resources. Problems such as groundwater contamination, emission of greenhouse gases, drying up of groundwater table and soil degradation due to excessive use of chemical fertilizers, need to be tackled efficiently so that the future demands on agriculture are fulfilled. Traditional farming practices when combined with new technological tools can enable an increase in the crop productivity in a sustainable manner. Use of modern farming tools along with traditional tools has given rise to a new concept in agriculture called as Precision Agriculture.

1.1 Precision Agriculture

Traditional farming practices take into consideration the field as one whole unit and based on this, all the required inputs for crop production are applied. This results into either over use or under use of fertilizers and water, thus leading to environmental
degradation. Modern agricultural techniques consider a large farm to be made up of small units and accordingly apply the inputs based on local requirements. The technique of taking into consideration the spatial and temporal variability exhibited by soil within a field and the site specific management of resources is called Precision Agriculture or Precision Farming. With advancements in the field of information technology, it is possible to use various tools like Global Positioning Systems (GPS), data sensors etc. to get precise information regarding a particular location in a field and accordingly adjust the application of the inputs. This technique not only enhances the crop productivity and profitability, but also helps to utilize agricultural resources in a more sustainable manner.

Precision farming techniques are cost effective, can produce high yield and increase profitability, as compared to traditional agricultural practices which are time-consuming, labor intensive and expensive. But still there are some constraints on the implementation of precision farming techniques on a large scale. These constraints are the initial setup cost and unavailability of sensing systems which are fast and accurate [3]. Since precision farming is based on site specific decision making, precise information is a must for the decision making. Information related to soil such as moisture content, texture, physical and chemical composition, crop conditions, climatic conditions, etc. is very much essential in precision farming. The collection and processing of data in precision farming is done through the use of various technologies that are discussed as follows.

1.1.1 Global Positioning System (GPS) Receivers

GPS is a satellite based navigation system that provides precise, three dimensional positioning information in real time, while in motion under any weather conditions. GPS was originally developed for military use, but was later on made available to the public,
and lately farmers have been using it for site specific management of the farm. GPS allows creating maps of crops and soils. Use of GPS receivers enables the users to perform necessary action on that particular location of the field. GPS receivers may be either carried on field by the user or may be mounted on a vehicle for the identification of the site. GPS in combination with other technologies can be used in wide range of applications such as yield mapping, variable rate application, tillage adjustments, etc.

1.1.2 Geographic Information Systems (GIS)

GIS is used to manage and analyze site specific data related to crop productivity and other factors related to agronomy. It is a computerized system of storage and retrieval of data that integrates all types of information related to a field and interfaces this information with other decision support tools. Information such as yields, yield maps, soil survey maps, remote sensing data, crop data, soil nutrients, etc. are stored in the computer and through the use of procedures the information is processed and analyzed to produce maps. These maps are then used by farmers in the decision making. A large number of Farm Information Systems (FIS) are available that use simple software for creating a farm level database. One example of FIS is LORIS (Local Resources Information System) that enables the importation of data, and generates various maps like digital agro-resource map, operational map, etc. A GIS database application for farming can provide information on field topography, types of soils, soil testing, crop yield, irrigation and fertilizer and pesticides application rates.
1.1.3 Remote Sensing

Remote Sensing technology captures information about an object from a distance without making physical contact with the object. Remote Sensing system uses a sensor for acquiring the information of an object and a sensor platform for mounting the sensor which may be a hand held device or a satellite or an aircraft. Some spacecraft platforms currently being used are Indian Remote Sensing Satellites (IRS) and French National Earth Observation satellite (SPOT). Issues related to plant health due to various soil conditions like moisture content, nutrients, compaction etc. can be easily detected through the use of overhead images. Cameras with high spectral resolution are widely used to collect information from satellites. Infrared images captured by electronic cameras are found to have high correlation with healthy plant tissues. Factors causing crop stress can be easily identified through remote sensing, thus enabling the user to devise a site specific plan for the remedial action. Remote Sensing has a huge potential in precision agriculture since it can be used to monitor spatial variability with time at high resolution. The use of Remote Sensing is found to have some inherent limitations such as the need for instrument calibration, atmospheric correction, processing of images from airborne video and digital cameras. Remote Sensing technology can be successfully implemented in precision farming only if it has the following characteristics: low turnaround time (24-48 hours), high spatial resolution, high spectral resolution (<25nm), high temporal resolution (minimum 5-6 data per season), low cost of data (approx. Rs.100/acre/season) and the interpretation of results in simpler formats [4].
1.1.4 Variable Rate Technology (VRT)

Variable Rate Technology is based on yield maps that are used to form prescription plans for application of inputs for a specific site. It makes use of automated systems that are used in wide range of farming operations. Some of these operations include seeding, application of fertilizers and pesticides, etc.

1.1.5 Data Sensors

Various sensors are used to measure crop and soil related data such as humidity, crop health, texture, etc. Remote and proximal sensing technologies are widely used to generate high density data that provides field information. Remote sensing technologies use sensors placed on aerial systems or spacecrafts whereas proximal sensing technologies generate field information by placing sensors at a close range or in contact with field surface. Different technologies such as electrical, electromagnetic, photoelectric, ultrasound are used for the measurement of soil and crop parameters. The data collected through these sensors are analyzed using appropriate software and used in the decision making of variable rate application [5].

1.1.6 Precision Farming in Developed Nations

In developed countries farmers own large areas of land typically 10-100ha or more. Agriculture in these countries has shifted from the use of traditional methods to mechanized farming to the use of precision farming technologies. Farmers in USA and Canada started precision farming through the use of GPS technique with a yield monitor to generate yield maps. More recently the focus of precision farming has shifted towards
the use of variable rate applicators, through which the application of fertilizers, seeding and irrigation can be controlled.

In Europe, the development and advancement of precision farming is less as compared to USA. This is mainly because of the fact that the sizes of farms in Europe are relatively smaller. In case of Japan where the farm size is small, most of the researchers and the land owners have the perception that the use of precision farming technologies in small farms is not beneficial.

Although precision farming is widely used in developed nations, still its use is limited for various reasons such as the cost effectiveness, requirement of skilled manpower to handle large amounts of data and information. For a more widespread use of precision farming, there is a need to develop user friendly simulation models and decision support systems [6].

1.2 Agricultural Scenario in India

Agriculture is still considered as the backbone of Indian economy, even though its contribution to the overall GDP has decreased from 30 percent in 1990-91 to around 15 percent in 2011-12. This is because roughly half of Indian population is dependent on agriculture for its livelihood. A mere 1 percent growth in agricultural sector is found to be effective in reducing the poverty of a country as compared to the growth obtained in non agricultural sectors. Considering the fact that India has the largest number of poor and malnourished people in the world, agriculture plays an important role in the upliftment of these people, thus reducing poverty. The Green Revolution in India brought a great change in agriculture, but still India lags behind by two third of the world average in
terms of per capita food grain availability. Green Revolution was seen to be more effective in only five states of India namely, Haryana, Punjab, Himachal Pradesh, Madhya Pradesh and Uttar Pradesh which has a combined population of just 1/3rd of the country’s population. Even though Green revolution in India has made it self sufficient in terms of food production, still it is far behind as compared to the world’s highest productive countries. The negative impact of Green Revolution can be seen in terms of land degradation and environmental pollution. Of the total geographical area of 328.7 million ha, about 182 million ha is rendered to be non arable due to land degradation. India contributes to 17 percent of world population, with a geographical area of 2.5 percent, 4 percent of carbon emission, 1 percent of gross world product and a 2 percent of world forest area. This shows that the availability of natural resources in India is limited and needs to be utilized in a sustainable manner. Therefore, the need for implementation of precision farming in India is urgent. This will not only help in the increase of crop productivity, but will also enable the farmers to use sustainable practices in agriculture, thus enabling efficient utilization of resources [7, 8].

Precision Farming is still in its developmental stage in most of the developing countries, though it is widely being practiced in developed countries. The challenges that lie ahead of India in the implementation of Precision Farming are: small land holdings which may not be cost effective for implementing precision farming, lack of proper infrastructure, lack of skills and technical knowledge and lack of initiatives by the government. Various agricultural universities in the country through different projects are trying to study the feasibility of precision farming in India. The Tata Kisan Kendra (TKK) under the auspices of Tata Chemicals (TCL) has initiated the concept of Precision
Farming by providing extension services to farmers. Remote sensing technologies are used for soil analysis, gather information regarding crop health, pest attacks and in the prediction of final crop yield. The extension services provided by TKK help the farmers to adapt quickly to the changed conditions, which results in the yield of healthier crops, higher output and income to the farmers. TKK also provides loans and insurance for crops against natural disasters [9].

Tamil Nadu Agricultural University in collaboration with the State Government started the drip irrigation project in 2004-05 initially for an area covering 250 acres, extended to 500 acres in 2005-06 and 250 acres in 2006-07. The results showed that it not only reduced the water and fertilizer usage but also increased in higher crop yields. The Space Application Center, Ahmedabad in collaboration with the Central Potato Research Station at Jalandhar, Punjab started a project to study the role of Remote Sensing to map the soil variability in terms of space and time. Similarly, the Indian Agricultural Research Institute conducts various experiments to study the feasibility of Precision Farming. Experiments on variable rate input application in different cropping systems have been started by Project Directorate for Cropping Systems Research (PDCSR) Meerut and Modipuram in collaboration with Central Institute of Agricultural Engineering (CIAE), Bhopal. In Tamil Nadu, a village has been adopted by M.S. Swaminathan Research Foundation, Chennai in collaboration with NABARD for conducting experiments on variable rate input application [7].

1.2.1 Agriculture in the State of Goa

Goa located on the west coast of India is the smallest state spread over an area of 3.61 sq.km. Goa is surrounded by Sahyadri mountains on the east and the Arabian sea on the
west and shares its boundary with Maharashtra on the north and Karnataka on the east and the south. Goa was ruled by Portuguese for nearly 450 years and was liberated in 1961. Tourism and mining are the main industries supporting Goa’s economy. The agricultural sector in Goa provides livelihood to around 12 percent of the population. There are some major changes in the agricultural sector in Goa from the last 50 years of liberation. Agriculture was the main occupation of nearly 70 percent of the population at the time of liberation which has been reduced to just 12 percent. Paddy was the main crop followed by cashewnut and coconut. The cropping pattern since then has changed with cashew being cultivated in nearly 55000ha, paddy covering around 31000ha and coconut cultivation covering an area of around 25100ha. Horticultural crops are also gaining popularity due to its high return and lower risk involved. Apart from these crops, pulses and groundnuts are also cultivated [10].

Goa has different types of soils ranging from red lateritic in lowland and uplands, sandy in the coastal areas and mostly alluvial along the riverbanks. Soils in Goa have unique characteristics and a varying fertility status. Around 81 percent of the soil is lateritic having good amount of nitrogen and organic matter but poor in potash, phosphorous and lime. They are also highly acidic and well drained. Around 8 percent is alluvial and loamy found along the riverbanks and the remaining 11 percent is sandy. These soils are also highly acidic and are found to be deficient in potash and phosphorous but have sufficient amount of organic matter. The soils and weather of Goa support a wide range of crops and vegetation [11].
1.2.2 Precision Farming in The State of Goa

The Directorate of Agriculture, Government of Goa, Indian Council of Agricultural Research (ICAR), Goa, Zuari Agro Chemicals Ltd., are some of the institutes that have taken an initiative in the implementation of precision farming in the state of Goa. The Directorate of Agriculture has a number of ongoing projects that can help farmers to improve the quantity and quality of the crop yield. Some of the ongoing projects are as listed below[12]:

- Setting up of agro services that can provide assistance to farmers related to machinery and infrastructure.
- Promotion of combines for paddy harvesting
- Soil and nutrient mapping
- Assistance for use of soil conditioners/ soil amendments
- Assistance for use of soil micronutrients
- Mechanization in agriculture

The ICAR has also initiated projects in the state for the betterment of farmers. Some of these are as follows:

- Demonstration of precision farming technology in banana, papaya and pineapple.
- Development of comprehensive e-agriculture portal for information and knowledge sharing in Goa.
- Soil Test Based Recommendation program- software package that prescribes the amount of fertilizers to be used based on the soil fertility reports and the crop yield target. It also estimates the cost involved [13].
Zuari Agro Chemicals Ltd. have started a program for farmers titled Goa Agriculture Initiative (GAIN) with the aim of making agriculture in Goa self sufficient and resilient. The farmers are provided support in terms of assisting the farmers to adopt right technologies so as to increase their farm outputs [14].

### 1.3 Soil Sensing in Precision Farming

Soil is an important natural, non-renewable resource on which agriculture is based. Soil is a complex site-specific system which shows wide variations with space and time. The concept of soil health is very important for the sustenance of agriculture. Healthy soils function as a balanced living system and are capable of sustaining plant and animal production, can maintain and enhance the quality of air and water and can promote the healthy living of animals and plants. Therefore, soil can be considered as the basis of an agro-ecosystem of a nation for the production of food, feed, fiber and fuel. The quality of soil changes with time either because of natural events triggering the change or because of human activities. Though the quality of a soil with regards to its physical, chemical and biological properties is dependent on the climatic and ecosystem of a particular location, the maintenance and the enhancement of the soil quality can be in the control of the landowner [15].

#### 1.3.1 Components of Soil

Soil consists of four important parts- mineral solids, water, air and organic matter. Mineral solids in the form of sand, silt and clay consists of silicon, oxygen, aluminum, calcium, potassium and magnesium. The soil water which consists of dissolved nutrients is the main source of nutrients for the plants. The air provides oxygen to the roots and
removes excess carbon dioxide from root cells. The minerals and organic matter combine together to form aggregates which create a soil that contain more pores for water storage and gas exchange [16].

Soil fertility depends on the physical, chemical and biological characteristics of a soil. For example, water retention capacity of the soil, organic matter content, texture, acidity all these factors contribute to the fertility of soil. Plants need at least sixteen elements for its growth and completion of its life cycle. Plant growth is basically a complex process wherein the synthesization of water, solar energy, carbon dioxide and nutrients take place. Carbon, hydrogen and oxygen are the non mineral elements supplied through air and water and are required in large amounts as compared to the other 13 elements. The remaining 13 elements are utilized by plants in the form of minerals supplied from the soil or externally through fertilizers. The amount of nitrogen, potassium and phosphate required for plant growth is sufficiently large and are called as primary nutrients. The other less intensively used nutrients also called as secondary nutrients consist of sulphur, calcium and magnesium. Apart from these soil consists of large number of micronutrients such as chlorine, manganese, zinc, iron, boron, molybdenum and copper which also influence the plant growth. These nutrients although in very small amounts are essential for the proper functioning of plant metabolism. Plant growth can be hampered in the absence of these nutrients whereas if present in large amounts can be toxic to both the plants as well as its consumers. All these nutrients are taken up by plants from the soil either through their roots or through their leaves. Factors such as soil pH, microbial activity, and chemical properties of the elements present in the soil and the physical
conditions of the soil such as aeration, moisture, temperature and compaction determine the availability of nutrients to the plants [17].

1.4 Importance of Soil Testing

Plants synthesize the nutrients available in soil along with the other elements for its growth. Continuous crop production reduces the reserves of nutrients required for plant growth in the soil. Thus, proper soil nutrient management is required so as to replenish the soil with the lost nutrients for continuous plant growth. This not only helps in the conservation of soil but also helps in preventing economic inefficiency and damage to the environment.

In a soil nutrient management program, soil testing and proper interpretation of results form an important tool. Periodic assessment of soil to study its condition is very important in agriculture for the production of healthy crops. The conventional soil testing method involves taking soil samples from a field to a laboratory and doing the analysis. Based on the results a soil report is generated. There are certain limitations on using the laboratory testing such as different laboratories use different approaches in the interpretation of results and recommendation of fertilizers. Also, these methods are time consuming, costly and labor intensive. Hence the conventional soil testing methods are being slowly replaced with real time soil sensors that combine information from other sources and generate a soil testing report. These are fast, portable and cost effective. Since the principle of precision farming is based on site specific management, these sensors are effective in generating the soil reports at a much faster rate. Also, the number of samples for testing can be quite large as compared to the conventional methods, thus
giving more accurate soil reports. Various researchers around the world are developing soil sensors that can be effectively used in precision farming. Some of these sensors are commercially available, while some are still in the research stage. Based on the principle of working of these soil sensors, they can be broadly classified as follows:

1.4.1 Electrical and Electromagnetic Sensors

These sensors are based on the ability of a medium to conduct current or store electrical charge that can affect the behavior of an electrical circuit. The soil acts as a conducting medium and depending on the physical and chemical composition of soil, the circuit behavior changes, which can be used for measuring the required output. These sensors are used for the measurement of soil Electrical Conductivity (EC), from which various other soil parameters, can be measured through correlation. Two techniques are used for soil EC measurements: contact and non-contact.

In case of contact measurement, electrodes are used through which current from a source is injected into the soil. The voltage drop between the source and sensing electrode is measured which depends on the conductivity of the soil. The effective measurement depth depends on the distance between the two electrodes, thus by using more than two electrodes it is possible to measure multiple depths simultaneously. The working principle of contact sensor is as shown in figure 1.1.
The non-contact EC sensor works on the principle of electromagnetic induction and uses two coils placed just above the soil surface. An Alternating Current (AC) signal passing through the transmitting coil induces current into the soil, which induces a secondary current into the receiving coil. The depth up to which an effective measurement can be taken depends on the how the coils are oriented and also on the distance separating the two coils. These sensors are commercially available and are found to give fast response, durable and low cost. They are widely used for on-the-go soil EC mapping. Figure 1.2 shows the working principle of non-contact.
Studies for the comparison of contact and non contact EC sensors are conducted by various researchers [18-20]. Similarities in map patterns and high correlation between collocated points were reported. A study conducted on electrical conductivity measurements obtained through non contact electromagnetic induction sensor showed that the operation speed and height, topsoil depth, soil moisture and temperature and also the drift in instrumentation has a significant effect on the measurements [21]. The heterogeneous nature of soil in a field can be observed through the measured values of electrical conductivity or resistivity. The measured values are found to be affected by various soil parameters such as salinity, texture, organic matter content, soil moisture content and depth of clay pan [22]. Since a single measurement is not sufficient to predict several properties simultaneously various researchers have attempted multiple measurements. A study conducted using laboratory testing method for simultaneous measurement of soil conductive and capacitive properties showed that through the application of frequency response analysis, soil moisture and salinity can be separated as $r^2$ as 0.73 and 0.56 respectively [23]. A similar study conducted under controlled soil density and depth conditions obtained $r^2$ values for soil moisture and salinity to be 0.88 and 0.83 respectively [24]. Capacitance and dielectric based measurements were used for determining soil moisture content in another study [25]. A sensor for on-the-go measurement of soil moisture was developed in the form of a tine shape, which showed that 84 percent of the sensor variance is because of differences in moisture content [26]. The electrical and electromagnetic sensing technologies can be summarized as shown in table 1.1.
Table 1.1: Electrical and Electromagnetic Sensing Technologies.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Working Principle</th>
<th>Development status</th>
<th>Results</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Contact based EC sensors (use of spike wheels or rolling coulters)</td>
<td>Commercial implements available, numerous research projects</td>
<td>Soil texture determination gives the best result. Stable filed patterns obtained, indirect prediction of soil nitrate, effects of organic matter, moisture and salinity.</td>
<td>[27] [28] [29]</td>
</tr>
<tr>
<td>2.</td>
<td>EC sensors based on Electromagnetic Induction (non contact)</td>
<td>Commercial implements available, large number of research projects</td>
<td>Stable field patterns having high correlation with contact sensors. Effect of operational speed and height of measurement.</td>
<td>[30]</td>
</tr>
<tr>
<td>3.</td>
<td>Capacitance and EC contact sensor</td>
<td>Laboratory testing under controlled conditions</td>
<td>Can measure soil salinity and moisture simultaneously.</td>
<td>[31]</td>
</tr>
<tr>
<td>4.</td>
<td>Capacitance contact sensor</td>
<td>Field tests, commercial circuits available</td>
<td>Measurements can be correlated with volumetric moisture content</td>
<td>[32]</td>
</tr>
</tbody>
</table>

### 1.4.2 Optical and Radiometric Sensors

These sensors are based on the measurement of the amount of absorption, reflection or transmission of light by or through a medium under study. In agriculture, these sensors use soil as the medium and the spectral response obtained is used to characterize some component of soil. Spectroscopic techniques in the near infrared (NIR), mid infrared (MIR) and visible regions are widely used for the characterization of soil. Studies have shown that the effect of various soil properties in different spectral regions changes by certain degree and hence these sensors have the potential of using a single sensor for studying several effects. Using optical sensors soil properties like organic matter, CEC, soil moisture, various minerals like nitrogen, calcium etc. can be estimated. Radiometric sensors include microwave sensors and Ground Penetrating Radar (GPR) and are found
to have potential applications in the measurement of soil water content and the geophysical soil structure. GPRs can be used to map soil properties like organic matter, soil texture, thickness and depth of soil horizons and water tables which means they have the potential in management of water resources. Visual and NIR spectral response of soil have been successfully used in the prediction of soil properties like texture, organic matter, CEC etc. with the application of appropriate data analysis techniques. Some researchers have also successfully correlated soil chemical properties like soil nitrate and pH with the soil reflectance. Thus, optical and radiometric sensors provide a rapid and non destructive approach in the characterization of various soil properties. Instruments using GPR and spectrometers in the visual and NIR range are commercially available. The technologies used for optical and radiometric sensors can be summarized as shown in table 1.2.

**Table 1.2: Optical and Radiometric Sensor Technologies**

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Working Principle</th>
<th>Development status</th>
<th>Results</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.</td>
<td>Hyperspectral visual and NIR soil reflectance sensor</td>
<td>Lab. Studies, field tests, commercial spectrometers, data processing algorithms</td>
<td>Correlation with soil EC, pH &amp; nutrients. Correlated to OM, texture, moisture &amp; CEC.</td>
<td>[34-36]</td>
</tr>
<tr>
<td>3.</td>
<td>Hyperspectral visual &amp; MIR soil reflectance sensor</td>
<td>Laboratory test</td>
<td>Soil nitrogen correlation with mineral Na.</td>
<td>[37]</td>
</tr>
<tr>
<td>4.</td>
<td>Microwave sensor</td>
<td>Theoretical study</td>
<td>Correlation with soil moisture</td>
<td>[38]</td>
</tr>
<tr>
<td>5.</td>
<td>GPR</td>
<td>Field tests, commercial installments available</td>
<td>Correlation with soil moisture, studies in geophysical soil lab.</td>
<td>[39]</td>
</tr>
</tbody>
</table>
1.4.3 Mechanical Sensors

These sensors are used to obtain the mechanical characteristics of soil such as compaction. Compaction in soil may occur due to natural process of drying and wetting or it may be due to human induced causes such as the use of heavy farm machinery and inappropriate choice of tillage systems. Compaction makes the soil particles to come closer to each other which reduce the air permeability and water infiltration in the soil. This results into restricted root growth rate and restricted accessibility to nutrients for the plants, thus resulting into reduced crop yield. Measurement of compaction is done by finding the resistance of soil to penetration through the use of a standard vertical cone penetrometer. Cone penetrometers are time consuming and produce highly variable results and hence cannot be used in real time systems. Alternative methods like strain gauge and load cells are used to measure forces acting on tillage tools. These methods are found to be ideal for using in real time systems as they are fast, robust and inexpensive and can be easily interfaced with data acquisition systems. The various technologies used in the development of soil mechanical sensors are summarized in table no. 1.3.
Table 1.3: Mechanical Sensor Technologies

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Working Principle</th>
<th>Development status</th>
<th>Results</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Mapping using draft force</td>
<td>Commercial implements available in most modern tractors</td>
<td>Can be used to infer pre-tillage conditions</td>
<td>[40,41]</td>
</tr>
<tr>
<td>2.</td>
<td>Use of load transducers to measure total draft</td>
<td>Commercial field mapping, field tests</td>
<td>Correlation with compaction for specified texture and moisture</td>
<td>[42]</td>
</tr>
<tr>
<td>3.</td>
<td>Single depth horizontal penetrometer</td>
<td>Field tests</td>
<td>Correlation with cone penetrometer</td>
<td>[43]</td>
</tr>
<tr>
<td>4.</td>
<td>Use of an array of load cells and independent</td>
<td>Field tests, Commercial field mapping</td>
<td>Determination of soil mechanical resistance at varying depths, correlation with vertical cone penetrometer</td>
<td>[44-46]</td>
</tr>
<tr>
<td></td>
<td>load cells and independent horizontal soil penetrometers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>An implement for deep tillage using load cells and strain gauges</td>
<td>Preliminary field tests</td>
<td>Depending on the variation of soil mechanical resistance with depth can provide real-time correction of tillage depth</td>
<td>[47]</td>
</tr>
</tbody>
</table>

1.4.4 Acoustic and Pneumatic Sensors

These sensors can be used as an alternative approach for differentiating soil physical and mechanical characteristics to electrical, electromagnetic, mechanical, optical and radiometric sensors. Acoustic sensor measurements can be used to correlate soil texture and compaction. These sensors consist of a shank having a rough surface and a hollow cavity which is equipped with a microphone that records the sound produced through the interaction of soil and the shank. Based on the frequency of recorded sounds, soils can be categorized. Pneumatic sensors are based on the pressure required to force a given flow of air into the soil. The sensor consists of an air injector that is placed in direct contact
with the soil and the resulting air pressure and flow are compared with the air permeability. This sensor can be used for the detection of changes in soil compaction, moisture content and soil texture. They are still under study and commercial implements are not yet available. The technologies used in the development of acoustic and pneumatic sensors along with their developmental status are summarized in table no.1.4.

Table 1.4: Acoustic and Pneumatic Sensor Technologies

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Working Principle</th>
<th>Development status</th>
<th>Results</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Soil shank equipped with microphone</td>
<td>Soil bin tests</td>
<td>Results found to have correlation with soil clay content</td>
<td>[48]</td>
</tr>
<tr>
<td>2.</td>
<td>horizontal cone penetrometer equipped with microphone</td>
<td>Soil bin tests</td>
<td>Detection of plow pan depth through correlation with cone penetrometer</td>
<td>[49]</td>
</tr>
<tr>
<td>3.</td>
<td>Air pressure transducer</td>
<td>Field tests</td>
<td>Based on the structure/compaction, moisture and soil type, separation of different tillage treatments</td>
<td>[50]</td>
</tr>
</tbody>
</table>

1.4.5 Electrochemical Sensors

These sensors are widely used in the measurement of soil chemical properties. They are based on the measurement of potential difference between a sensing electrode and a reference electrode, produced due to the activity of targeted ions. Ion Selective Electrodes (ISE) and Ion Selective field Effect Transistors (ISFET) are two widely used electrochemical sensors for the measurement of soil pH and soil nutrient content. Conventional laboratory testing methods for soil chemical analysis have been making use of ISE’s from a quite a long time and are found to be quite accurate in their measurements. ISFET’s are relatively new as compared to ISE’s and are much better than
ISE’s in terms of small size, fast response, better signal-to-noise ratio, low output impedance and the possibility of integrating several sensors on a single electronic chip. The limitation of electrochemical sensors is that the time required for the sensing electrode to reach equilibrium with measured soil or soil solution is quite significant, thus limiting the use of these sensors in real time sensing. Also, the sample preparation may be quite tedious if the laboratory methods of testing are to be replicated in a real time measurement system. The prototype development for these sensors is quite complex and are still under study. Only pH sensors using this technique are currently commercially available [51]. The electrochemical sensors used for soil sensing along with their current status is summarized in table no. 1.5.

**Table 1.5: Electrochemical Sensor Technologies**

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Working Principle</th>
<th>Development status</th>
<th>Results</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Ion selective electrodes for direct measurement of ion activity</td>
<td>Commercial implements available, field tests</td>
<td>Correlation with residual nitrate content, soluble potassium, and pH, on the go soil pH mapping commercially available</td>
<td>[52,53]</td>
</tr>
<tr>
<td>2.</td>
<td>Rapid extraction of soil cores</td>
<td>Laboratory tests</td>
<td>Potential for reducing lag time between sample collection and sensor output</td>
<td>[54]</td>
</tr>
<tr>
<td>3.</td>
<td>Sampling, conveying, extracting and measuring unit</td>
<td>Field and laboratory tests</td>
<td>Correlation with nitrate content, required hardware improvements</td>
<td>[55]</td>
</tr>
<tr>
<td>4.</td>
<td>Ion-selective field effect transistors (ISFETs) with flow injection analysis</td>
<td>Laboratory tests</td>
<td>Correlation with soil nitrate concentrations,</td>
<td>[56]</td>
</tr>
</tbody>
</table>
A large number of soil sensors are being developed to provide real time measurements of various soil properties. Though commercial implements of some of the sensors are available, they do not provide direct measurement of a specific soil property. Commercial implements of electrical and electromagnetic soil sensors are used in the generation of EC maps on the go and can be used to find heterogeneity existing in a field. These maps can be used in controlling the inputs applied to the field. Researchers are currently focusing on the development of systems where multiple sensors are integrated on to a single unit. The data obtained from these multiple sensors can be used in the prediction of selected soil attributes and can support site specific management.