Variable rate fertilizer application technology for nutrient management: A review

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Abstract: The efficient and effective application of fertilizers to crops is a major challenge. Conventionally, constant rate or equal dose of fertilizer is applied to each plant. Constant rate fertilizer application across entire field can result in over or under incorporation of nutrients. Fertilizer application is influenced by soil parameters as well as geographical variation in the field. The nutrient management depends on selection of nutrient, application rate and placement of nutrient at the optimal distance from the crop and soil depth. Variable rate technology (VRT) is an input application technology that allows for the application of inputs at a certain rate, time, and place based on soil properties and spatial variation in the field or plants. There are two approaches for implementing VRT, one is sensor based and another is map based. The sensor based approach; with suitable sensors, measures the soil and crop characteristics on-the-go calculating the amount of nutrients required per unit area/plant and micro controlling unit which uses suitable algorithms for controlling the flow of fertilizer with required amount of nutrient. In map based approach; Grid sampling and soil analysis are used to create a prescription map. According to the soil and crop conditions, the microcontroller regulates the desired application rate. The sensor-based VRT system includes a fertilizer tank, sensors, GPS, microcontroller, actuators, and other components, whereas the map-based system does not require an on-the-go sensor. Both approaches of VRT for fertilizer application in orchards and field crops are reviewed in this paper. The use of this advance technology surely increases the fertilizer use efficiency; improve crop yield and profitability with reduced environment impacts.

Keywords: nutrient sensor, prescription map, spatial variation, VRT

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1 Introduction

The important phase for the maximizing quantity and quality of crops is nutrient application[1]. The demand of increased population can be achieved by increasing agriculture yield through effective nutrient application[2]. Fertilizers being a costly input, it requires scientific approach while using it. The use of crop nutrients according to the actual need of the crop growth stage is worthy practice[3,4]. Fertilizers can be administered to agricultural fields through three distinct application methods: manual application, utilization of agricultural machinery, or incorporation via irrigation systems, known as fertigation. Moreover, fertilizers can be distributed evenly across the entire field or selectively targeted to specific areas within the field[5,6]. China is the world's largest consumer of fertilizers followed by India and Brazil[7]. In the 2019-20 fiscal year, world's total nutrient consumption ($N+P_2O_5+K_2O$) was 201.84 Mt[8].

The application of fertilizers to agricultural fields through modern methods offers numerous advantages, including the enhancement of soil properties and plant growth patterns, cost savings in production, and heightened productivity[9]. When fertilizers are evenly distributed, certain areas of a field may experience insufficient fertilization, while others might face excessive fertilization[10]. Typically, inadequate fertilization can lead to reduced yield and compromised quality, while excessive fertilization poses environmental risks, such as deteriorating water quality and promoting weed growth. This can result in increased costs and reduced profitability[11].

The increased usage of nitrogenous fertilizers in agriculture has resulted in worrying levels of nitrate pollution in ground water in many sections of the country[12]. Nitrate-N contamination in agriculture is becoming a major concern around the world[13]. Water eutrophication is one of the negative consequences of heavy fertilizer use[1]. There are issues that arise as a result of the continued usage of inorganic fertilizers, as most farmers use fertilizer without first conducting a soil test[14,15].

Even under ideal conditions, plants use only 50% of nitrogenous fertilizers supplied to soil, with the remaining 2%-10%

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evaporating (2%-20%), reacting with organic compounds (15%-25%) in clay soil, and being transferred to ground water[16]. Mackown and Sutton[17] observed that nitrogen fertilizer use efficiency was 36.6% when nitrogen was broadcasted and climbed to 43-54% when nitrogen was side-dressed, depending on the site. It was also discovered that while using a mechanical spreader, more fertilizer went unused[18].

The proper assessment of required amount of nutrient for particular crop at different locations is important, which will assist to make customized dose of fertilizer that should be applied in a precise quantity, at required location. Nowadays, VRT is viewed as pivotal for the precise application of inputs[19,20]. The advent of VRT enables the implementation of precise fertilizer application methods tailored to address variations within agricultural fields[21]. VRT, is a method employed for the precise application of various agricultural inputs, including seeds, fertilizers, irrigation water, and tillage, tailored to the specific requirements of different management zones within agricultural fields. A management zone (MZ) represents a distinct portion of an agricultural field characterized by uniform factors and indicators. Consequently, the cornerstone of implementing precision agriculture (PA) techniques lies in dividing agricultural areas into multiple MZs based on factors such as soil mapping, crop growth, and yield[22,23]. Moreover, these systems offer the advantage of improving the efficiency of agricultural inputs by lowering costs and mitigating environmental pollution[24-26]. The sensor and map based approach are two basic techniques for adopting site specific management for variable rate input applications[27,28]. Combination of sensor-based systems with map overlay was also used in some fertilizer applicator[11,29]. Some researchers conceptualized variable rate fertilizer applicator based on map and sensor technologies to reduce fertilizer application overdose and underdose. A prescription map is developed based on grid soil sampling in map based methods. Also, it can be developed using available crop information like soil analysis, yield of previous crop, health conditions, and field topography, etc.[30]. The sensor-based method of VRT uses sensors for on the go measurement location-specific properties, and the collected information was used for regulating a variable rate input applicator on-the-go using a set of decision rules (or algorithms)[31]. For the successful implementation of VRT, several components were integrated as different sensors, electronic controllers, proportional control valves/actuators, object detectors etc. for application of inputs[29]. Crop yield is changing within the fields according to the spatial variation across the field, which affects fertilizer application rate[32].

This paper summaries the sensor-based and map-based approached of VRT for fertilizer application and various researchers' efforts for variable rate fertilizer application in orchards and field crops.

2 Concept of VRT

In VRT crop input utilization efficiency is increased by applying variable rate of input in the specific zone of field based on the soil conditions and requirements of the crop[33-36]. VRT application system integrated with fertilizer applicator for fertilizer application at particular location and time.

2.1 Sensor based VRT

The sensor based technique has the ability to change the rate at which inputs are applied without requiring any mapping[27]. Figure 1 depicts the sensor based variable rate application system. Crop inputs are on-the-go sensed by sensor, which are converted to suitable form using microcontroller and quantify the input application rate via hardware/algorithm interface[29]. The ability of on-the-go sensing devices that enable non-destructive and rapid assessment of soil variability is unrivalled, providing for precision plant nutrients control and implementation. On the flip side, sensor-based systems offer key advantages such as the capability to adjust the application rate of agricultural inputs without the need for prior mapping or extensive field data collection. They also enable real-time monitoring of crop and soil conditions and immediate application of agricultural inputs following measurements, eliminating delays. However, these systems do come with certain common drawbacks, including the initial high cost, the challenge of obtaining highly precise sensors, and the necessity for real-time data analysis and decision-making[37].

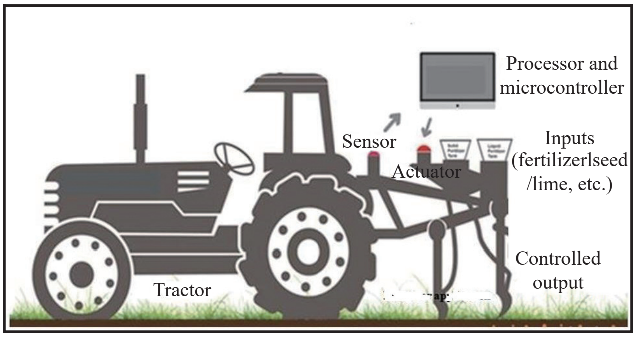

Figure 1 Schematic arrangement for sensor based variable rate application system

2.2 Map based VRT

Electronic data file i.e. prescription map generated based on grid soil sampling which contains detailed information about crop input i.e. fertilizer/water/seed application rate to the crop[36,38]. Figure 2 depicts the map based variable rate application system. Prescription map may also generated based on the information may be collected using the soil survey, conductivity maps and crop yield using remote sensing (RS)[39]. Arc GIS and MATLAB were also used for generation of electronic data file. Microcontroller extract information of prescription maps, which is used to regulate different inputs application i.e. fertilizers, seeds, pesticide choices, and application rate for effective proper input management[40].

Map based variable rate application include following steps, systematic grid soil sampling and nutrient analysis of sample, Creation of location specific prescription map of nutrients, Use set of programme (algorithms) for development of location-specific input application electronic file and controlled application rate of input using prescription map[27].

The main advantages of a map-based system include the ability to harness multiple sources of information, the wide availability of application systems for various agricultural inputs, and the adequate time interval between input sampling and application, which contributes to enhancing system accuracy[10]. Nevertheless, there are notable drawbacks to the map-based system. These include the labor-intensive and costly nature of soil and plant analysis, the temporal variability of soil and crop parameters between the time of sampling and application, and the necessity for specialized software tools to generate the requisite prescription maps[41].

3 Fertilizer application using VRT

Fertilizer application in agriculture is costly inputs. Traditional uniform application can lead to nutrient overuse or underuse, harming crop yield, quality, and the environment. Precision machinery, like Variable Rate Technology (VRT), addresses these

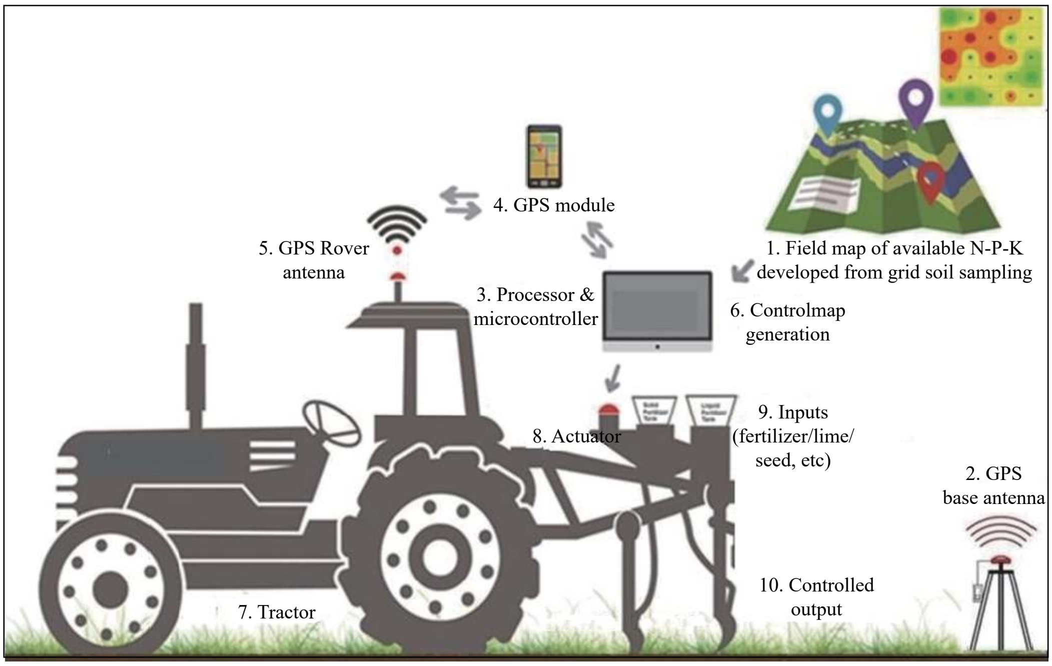

Figure 2 Schematic diagram of map based variable rate application system

problems. VRT tailors nutrient application to specific field locations, optimizing efficiency, increasing yields, and reducing environmental impact.

3.1 Real-time VRT for fertilizer application

In variable rate nutrient application, it is essential to acquire plant canopy data/soil data and calculate the amount of fertilizer to be sprayed/drop per nozzle/pipe in real time. While implementing sensor-based nutrient application, on-the-go sensor and control system is required for quantifying fertilizer need of crop and apply the required fertilizer rate at each specific location. Several sensors are commercially available for variable rate fertilizer application. Crop sensors such as Crop Circle and Green Seeker are routinely used to monitor plant canopy reflectance[42]. The reflectance of the plant canopy is measured in different bands using these sensors, which is used to calculate vegetation indices for indicating plant characteristics. The normalized difference vegetation index (NDVI) most commonly used index. NDVI is the ratio of difference between near-infrared (NIR) and red bands reflectance and sum of both the bands[42]. For crop management, a number of vegetation indices, such as reflectance band ratios and individual band reflectance, are used. It is critical to understand, how varied amount of nutrient is applied using sensor based approach of VRT. In case of Green seeker Sensor the sensor should place above 0.76-1.1 m from crop and for wider application like 12.2-15.2 m, used at least six sensors[30]. Hand held optical sensor i.e. green seeker is used for measurement of reflectance of crop area of 0.61×0.61 m^2 held 0.6 to 1.0 m above the crop[43].

It's also vital to understand the links between sensor measurements and plant requirements[42]. Determination of nitrogen concentration of crop canopy, the SPAD meter recorded correct observation[44]. This instrument can be adopted as a direct tool for measuring Nitrogen % and as an indicator for vegetation indices for image analysis[45]. In sensor-based applications, response time is a critical factor to consider. For on-the-go phosphorous application, Maleki et al.[46] employ a VIS-NIR spectrophotometer. The soil sensor was placed 0.91 m in front of the fertilizer outlets.

It's more difficult to write a prescription of sensor based approach of VRT for nitrogen applied to crop. Several scientists have devised several ways for this approach on cotton. Figure 3 depicts two nitrogen rate prescriptions with varied rates. The yield potential and a nitrogen-rich strip are the foundations of the Oklahoma (OK) technique. The nitrogen reference strip is the sole basis for the Missouri (MO) method. On the lower NDVI portions of the field, the MO technique apply a high N rate, while on the higher NDVI sections, no N is applied. The OK approach is more complicated, but because it is programmed into the on-board computer, it has no effect on the end user. The user must know the reference strip's NDVI, the nearby area's NDVI, the number of growing degree days, and the maximum yield potential[30].

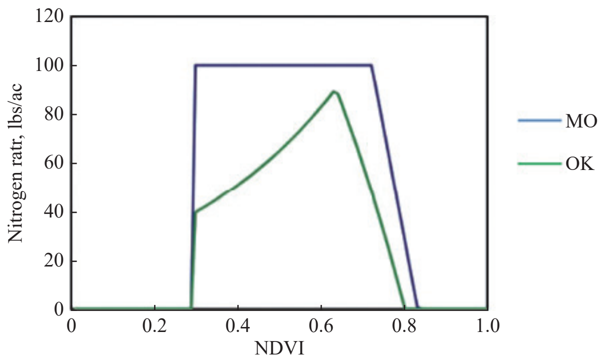

Figure 3 Determination of N-application using N-prescription maps using Missouri and Oklahoma methods (Taylor and Fulton[30]).

Mirzakhaninafchi et al.[47] developed variable rate nitrogen applicator for granular fertilizer in wheat crop. The handheld Greenseeker was used for real-time fertilizer application. It has maximum sensing width of sensor is 0.50 m and gives NDVI readings 0.00 to 0.99 from absent to highest value of N. They developed model for using sensor, in this model if NDVI reading is less than 0.35 then Nitrogen content is very less, for 0.35-0.95 crop become healthy and above 0.95 Nitrogen content is very high. According to this model they developed VRT applicator. The applicator consists of a Raspberry Pi and Arduino microcontroller board, MOSFET, Pulse width modulation (PWM) valve, power supply, hydraulic system, and the control software. The response time was found to be between 3.49 and 4.90 s at 0.83 m/s of vehicle speed. The Coefficient of Variation (CV) of discharged fertilizer at various outputs varied between 2.34 and 5.1%. Another successful example of a sensor-based Variable Rate Application (VRA) system for granular nitrogen (N) fertilizer was conducted by Heib et al. [48]. In their study, they employed two N-sensors installed on the tractor roof to gauge the N content by analyzing crop reflectance at specific wavelengths (670, 730, 740, and 770 nm). The system's control unit, which featured an electric actuator (electric motor), utilized a predetermined fertilizer rate to fine-tune the N fertilizer quantity throughout the application process.

Sui et al.[49], Sui and Thomasson[39] developed ground based sensor system to assess N-content of cotton plant on-the-go. The system consists of ultrasonic sensor, optical sensor, and data collecting devices. The optical sensor measured crop canopy reflectance in four wavebands: blue (400-500 nm), green (520-570 nm), red (610-710 nm), and near infrared (NIR) (750-1100 nm). Crop circle 210 sensor were utilized for on-farm investigation on sensor based VRT approach for N application for maize by Scharf et al.[50]. The sensor-based VRT raised profit by $42 per hectare per year and yield by 110 kg/hm^2·a and it reduces N use by 16 kg N/hm^2. Also, 25% reduction in N application was found.

Raun et al.[51] found that canopy spectral reflectance properties might be used to forecast grain yield potential in wheat. The NDVI was calculated using the reflectance readings. NDVI data and cumulative growth degree-days were used to calculate the yield potential. Using Nitrogen fertilisation optimization technique based on canopy optical reflectance, VRT for N-application in wheat which enhance Nitrogen use efficiency by >15% compared to uniform rate N-application. Biermacher et al.[52] and Boyer et al.[53] compared the profitability of a sensor based VRT approach for N application with traditional uniform N-application. The system's controller used the optical reflectance data to calculate N-application rate for each 0.37 m^2 grid on-the-go in situ and N-application depending on the rate using an algorithm. Grid size and algorithm for on-the-go N-application rate was modified for wheat. In comparison to traditional methods, they discovered that VRT approach for N-application is more profitable. Practicability of optical sensor for N-application management strategies in canola was investigated by Holzapfel et al.[54] Sensor-based N management reduction in N-application 34 kg/hm^2 without compromising crop production, compared to the traditional technique of N banding.

Maleki et al.[46] used a visible and near-infrared soil sensor to construct on-the-go variable rate phosphorus application, as shown in Figure 4. The Differential Global Positioning System (DGPS) receiver was utilised in conjunction with the Spectrophotometer and real-time soil sensor. To monitor soil reflectance spectra, a portable 'VIS–NIR spectrophotometer' with a measurement range of 305-1711 nm was mounted on the planter-applicator toolbar and connected to the on-the-go soil sensor.

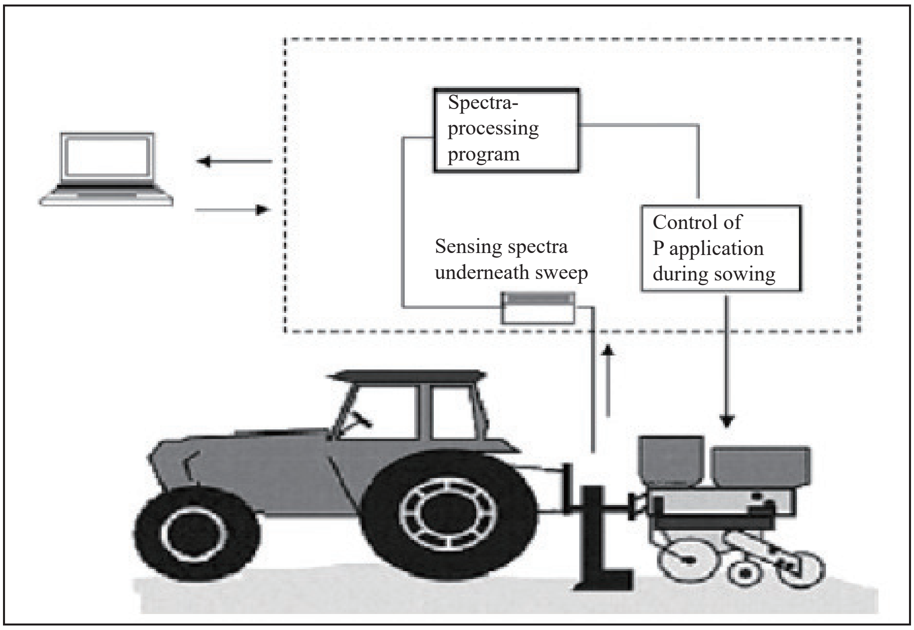

Figure 4 Schematic diagram of site-specific on-the-go phosphorus application during sowing (Maleki et al.[55]).

They observed that if there is a time lag between spectral soil scanning and fertilizer deposition, then adjustment is required. This must be compensated for accurate geo-referenced site-specific operation by placing the soil scanning device ahead at certain distance from the fertilizer outlets[46]. According to Maleki et al.[56] for a tractor speed of 0.28 m/s, the sensor should be placed 0.5 m from the fertilizer outlets, and for a speed of 1.95 to 2.22 m/s, to alleviate time delay, the sensor should be placed on front of tractor. The plant leaves were unaffected by the variable rate delivery of phosphate; the ultimate objective of this innovation can be the correction of Phosphorous non-uniformity in order to achieve uniform plant growth. This could affect field efficiency over the period of time. The greatest benefit from the Variable rate application of Phosphorous could be obtained after several years of obtaining a fairly consistent yield.

Schumann et al.[57] developed sensor-based variable rate granular fertilizer spreaders for citrus. While designing fertilizer spreaders they assumed that, absence of canopy means no roots, then fertilizer should not be applied. In comparison to mature trees, fertilizer should be used sparingly on small immature seedlings. Because canopy volume is related to tree height and fruit yield, "on-the-go" canopy sensors were used to measure tree height, and fertiliser rates were adjusted accordingly. For additional Nitrogen for maize, real-time Nitrogen sensing with a multispectral imaging sensor connected and fertilisation with a variable rate liquid application system were used by Kim et al.[58]. A nitrogen recommendation model was used to determine the estimated level of chlorophyll content and the amount of fertilisation. It was found that improved N status of the crop increase the yield uniformly.

Initial research in Oklahoma with the green active canopy sensor proved that active sensors are a viable method for improving nitrogen use efficiency in wheat[59], and nitrogen use efficiency was improved by 15% when compared to equal N-application[60]. The sensor based or on-the-go VRT is cheaper than map based VRT approach[47]. This is most accepted by the farmers but limitation in adoption of this is; only few Nitrogen sensors are available in market.

3.2 Map based VRT for fertilizer application

The map based VRT fertilizer application requires prescription map, VRA controller, software and GPS receiver. The GPS receiver identifies the VRA's location in the field when it travels across field. The VRA controller provides an electrical signal that controls a mechanical actuator to apply fertilizer at a specified rate to that specific location in the field based on spatial information from the GPS receiver and data from the prescription map.

Wahid et al.[28] developed fertilizer applicator based on VRT to oil palm. A basic GPS receiver was used to map the study location, and Loris software was used to build a variable-rate fertilizer map. Fertilizer placement accuracy of VRT system could be improved by the differential GPS receiver integrated with on-the-go error correction in GPS reading. The granular compound fertilizer performed better than the compact compound fertilizer for variable-rate application. VRT for granular fertilizer with 10 m boom was developed by Kim et al.[58]. This system comprised of soil characteristic map with a grid size of 10×10 m^2. The pneumatic applicator contained blow heads and metering mechanism. At a working speed of 0.2 to 0.8 m/s, the applicator applies 34 to 428 kg/hm^2 of granules. In the longitudinal and transverse orientations, the recorded CV values ranged from 2.9% to 15.3% and 11.2% to 13.1%, respectively, irrespective of operating speed. When the application rates were adjusted, the motor speed became stable after 0.64 to 1.01 s. The application rate's response times ranged from 1.5 to 3.03 s.

Radite et al.[61] developed an 8-bit Embedded System-based Variable Rate Fertilizer Applicator Module. A rotor type metering device was used to manage the required dose of application since it has a simple mechanism and can be powered directly by a DC geared motor. Forouzanmehr and Loghavi[62] developed and tested granular fertilizer based on map based approach of VRT for row crop. They used AVR microcontroller for controlling of metering mechanism using step motor and rotary encoder to getting position of applicator and speed. It was observed that, precision in rate was hampered due to speed and application rate while fertilizer type had a minimal effect. It was also noticed that, the precision of the application rate gets reduced with increased forward speed and application rate. The results show a statistically significant difference (p<0.01) in delay time when transitioning from a lower discharge rate to a higher one, with a delay time of 0.22 s, compared to the transition from a higher discharge rate to a lower one, which exhibited a shorter delay time of 0.15 s. The overall mean application rate error value was around 5.4%.

Wang et al.[19] used a Geographic Information System to develop a model for variable-rate fertilisation in maize. The maize variable fertilisation model is the establishment of nitrogen, phosphorus, and potassium levels based on a predetermined sampling point plot. The GPS based VRFA system was developed by Chandel et al.[63]. The prescription map (Grid size 8 m×8 m) was created using Arc GIS software. The DGPS was used to identify grids in real time. The feed roller exposure length was adjusted according to the microcontroller algorithm to modify the application rates. To adjust the exposure length of the flutes, 5.8 N·m (maximum) torque was required. In 1250 ms, the lever was moved from 0 to 32 mm of exposure length. A shift of one mm length of feed roller takes about 30 ms, with a range of 28 to 42 ms. The metering equipment was unaffected by the tractor forward speed. For exposure lengths of 0 and 44 mm, the fertilizer application rate was found to be 5 and 300 kg/hm^2, respectively. At the selected grid, the fertilizer application rate varies according to the required application rate, with a coefficient of variation of 11.7%-15%. High cost of the DGPS is system limitation. By substituting the DGPS unit with a local positioning system or a real-time soil nutrient sensor, the cost of the created system can be decreased.

Mohd et al.[45] developed variable rate fertilizer applicator for paddy farming. Field data were collected using gird soil sampling for ground truth data and UAV based image capturing for a broad area. It consisted of VRA controller which adjusts the required length of spreader orifice using metering mechanism for controlling desired rate when it moves from particular location. Mohd et al.[45] developed fertilizer calculation software. The developed software was based on GAI (Green Area Index) to determine the NPK fertilizer, urea and MOP (Muriate of Potash). The performance of variable-rate fertilizer applicator was evaluated by Ruixiu[64]. A total 120 samples were collected from eight rows of the fertilizer applicator at five different application rates and the data was analyzed to establish the uniformity and precision of the system's application rates. Chen et al.[65] developed a Variable-Rate Pulse Width Modulation (PWM) control system for a granular fertilizer applicator. This innovative control system incorporated several key components, including a microcontroller unit (MCU), a voltage detection unit, a speed measuring unit, and a positive voltage regulator. The system functioned by transmitting a signal to an electric drive, thereby adjusting the fertilizer application rate through the PWM method. In a more recent example, Song et al.[66] introduced a drone-based Variable Rate Application (VRA) system for fertilizers based on prescription maps. This advanced system primarily comprised components such as an electric step motor, a flight controller, and a spreading controller.

Alameen et al.[67] introduced a novel pneumatic control actuator designed to regulate the application rate of fertilizer in a seed drill. This innovative system relied on a prescription map and featured a specific schematic diagram for its operation. In a separate study by Reyes et al.[68], they developed and tested an automatic map-based system for Variable Rate Application (VRA) of granular fertilizers. This system utilized hydraulic technology and comprised several key components, including a GPS, a micro-controller equipped with an LCD display, a proportional flow control electric valve, a rotational speed sensor, and a hydraulic motor mounted on the fertilizer applicator shaft. The control unit of this advanced system was configured to receive a digital prescription map containing the desired application rates. It effectively controlled the flow of fertilizer by employing a bypass valve that directed the flow to the hydraulic motor, thereby adjusting the fertilizer rate to match the desired amount.

Intensive grid soil sampling is one of the most precise methods of assessing the variability of crop and soil data in precision agriculture[69]. But it is a time-consuming, labor-intensive, and expensive method[70,71], making it unsuitable for large scale adoption[72]. As a result, developing a faster method of obtaining spatial and temporal data for thorough variability mapping is desirable[69,70]. Using a DGPS receiver and real-time GPS reading error correction, the variable-rate fertilizer applicator's fertilizer placement accuracy can be enhanced[28]. Table 1 lists the various studies on the sensor based and map based VRT.

Table 1 Studies on the sensor based and map based VRT

Crop and fertilizer applied	Sensor/Map	Variables	Results/findings/suggestions	Reference
Wheat nitrogen (Granular)	N-sensor Greenseeker handheld sensor	1. N level (0, 90, 180, and 270 kg/hm²), 2. Response time and amount of applied N fertilizer	• Maximum sensing width of sensor: 0.50 m • Response time: 3.49 to 4.90 s at 0.83 m/s forward speed. • CV of discharged fertilizer: 2.34%-5.1%. • Sensor based applicator cost effective compare with Map based.	[47]
Urea at a time of sowing	Prescription map (Grid size 8 m×8 m)	1.Operating speed (0.55, 0.83 and 1.11 m/s) 2. Fertilizer to be dropped, kg 3.Actual fertilizer dropped, kg (Error %)	• Fertilizer application rate 5 and 300 kg/hm² for exposure length of 0 and 44 mm. • Coefficient of variation of 11.7%-15%.	[63]
Oil palm granular fertilizer NPK (12:12:17-2 +TE)	Long-range Radio Frequency Identification (RFID) tag use for identification.	1. Forward speed 2. Response time	• Response time: 2-3 s (depends on magnitude of change) • Alternative solution for geo-location determinationsforthefertilizerapplicatorintheplantationswherethepresenceoftreecanopieshashindered the use of GPS technology.	[18]
Direct soil application (Granular fertilizer)	Prescription map	1. Fertilizer type (triple super phosphate and urea) 2. Working speed (0.83, 1.66 and 2.5 m/s) 3. Application rate (75, 125 and 175 kg/hm²) 4. The difference between actual and target rates as a percentage.	• As forward speed increases, the precision of the application rate reduces. • Application rate error: 5.4%.	[62]
Corn nitrogen	Crop circle 210 sensor	-	˙Increase yield by 110 kg/hm² and profit by $42/hm². • Reduce Nitrogen use by 16 kg N/hm²	[73]
Cotton Nitrogen (Foliar)	N-sensor Greenseeker	-	• At least six sensors use for 12.2-15.2 m application. • Place Sensor above 0.76-1.1 m from crop.	[30]
Maize	Phosphorous (Granular) VIS–NIR spectrophotometer	Travelling speed and sensor distance	• Attached Soil sensor 0.91 m ahead of fertilizer outlets. • For 1 km/h tractor speed place sensor 0.5 m ahead. • For 7 and 8 km/h speed install the sensor in front of tractor.	[46, 56]
Paddy granular fertilizer (N:P:K)	Prescription map of 10 x 10 m grid size.	1. Operating speed 0.33 and 0.66 m/s 2. Discharge Rate, g/s	• Fertilizer application rate 34-428 kg/hm² of granules at 0.2-0.8 m/s working speed. • Response times 1.5 -3.03 s.	[58]
Wheat nitrogen	N-optical sensor	-	• Increase Nitrogen use efficiency by more than 15%.	[59]

3.3 Environmental impact of VRT

The amount of fertilizer applied to crop using VRT was reduced with increased utilization efficiency. The fertilizer applied in the effective root zone of crop and losses due to leaching, evaporation etc eliminated by VRT. The various researchers pointed out the environmental impact of VRT summarized in Table 2.

Table 2 Studies on the impact of variable rate fertilizer application an Environment and Economical benefits

Crop	Input/factor	Methodology	Environmental and Economical benefits	Reference
Potato	N-fertilizer and Pesticides	-	Save 25% pesticide and N-fertilizer.	[74]
Maize	Nitrogen phosphorous and potassium	Variable-rate fertilisation using geographical information system	Increase maize yield, cost savings, and environmental benefits achieved.	[75]
Pear orchard	Nitrogen	-	The consumption of nitrogen fertilizer has been reduced by 43%.	[76]
Citrus	Nitrogen	-	Save 40% of urea, which equates to US$138/hm² per year.	[77]
Citrus	Nitrogen	Categorized tree size according to their volume (0-240 m³).	Save 38%-40% urea.	[78]
Citrus	Nitrogen	-	Save approximately $55/hm² per year.	[79]
Wheat	Nitrogen	VR application using Pendulum Meter	Save 5 kg/hm² fertilizer. Increase yield up to 4.2%-4.4%.	[80]
Maize	Nitrogen	Used topsoil depth data for simulation model development.	Profit increase of up to $37.14/hm².	[81]
Maize	Nitrogen	To estimate N leaching, use the EPIC simulation model.	Reduce leaching up to 2.24-4.48 kg/hm².	[82]
Barley andpotato	Nitrogen	Field trials for estimate N leaching.	Reduce the possibility of N losses.Water quality should be preserved.	[83]
Maize	Nitrogen	Field trials for estimate N leaching.	Highest Nitrogen use efficiency.When compared to other treatments, this one has the least amount of leaching.	[84]
Potato	Nitrogen	Field trials. Measured N leaching with probes.	Surface soil had high NO_3–N flux.Subsurface soil NO_3–N flux stable.Reduce N leaching.	[85]
Wheat	Nitrogen	Use crop canopy reflectance readings to estimate top dress Nitrogen requirements on-the-go	Increase 15% yield. Reduce 44% N rate compared to a uniform N rate.	[86]
Wheat and barley	Nitrogen	Field trials. Measured reduced chemical loading.	Reduce Nitrogen by 36%.	[87]

4 Challenges and need

VRT has been used for nutrition management for over 25 years. In other countries, various types of equipment and control methods for variable rate fertilizer application are currently available commercially. In India, variable rate technique is still not frequently used in agricultural productivity. The delayed adoption rate could be attributed to a number of factors. The main reason for this is that there is no enough evidence that variable rate fertilisation can enhance crop net returns significantly. Variable rate fertilizer application has been shown to provide good economic returns in several studies; however, outcomes vary depending on how the technology is implemented and the actual field conditions. Producers are concerned about the uncertainty of profitability and the expense of implementation when investing in variable rate fertilisation technology. Further research in the following areas is needed to solve these concerns and speed the implementation of this technology:

a) Develop variable rate components at reasonable cost (i.e., Sensors, GPS, actuators, and controllers).

b) These components will be combined with current fertilizer application equipment

c) Develop low-cost and simple-to-use technologies for calculating site-specific fertilizer application rates and creating prescription maps.

d) Variable rate nutrient application over a long period of time has been studied for its economic viability and environmental effects.

5 Conclusions

Variable Rate Technology (VRT) is steadily gaining traction and delivering significant advantages in the management of agricultural inputs, there are still technical limitations that companies and researchers must address and improve upon. The importance of Variable Rate Fertilizer Application (VRFA) cannot be overstated, given its substantial economic and environmental implications.

The conclusions drawn from this study can be summarized as follows:

a) VRFA techniques for liquid as well as solid fertilizer have been developed based sensor and prescription map.

b) The most of the research have been done on variable application of Nitrogen. Sensors like Greenseeker, VIS-NIR Spectrophotometer, Crop Circle, SPAD meter are used for variable rate application. 40% of the fertilizers are save using VRFA.

c) Factors affecting performance of VRFA are operating speed, response time and application rate.

d) Despite the growing importance of VRA in modern agriculture, many existing VRA systems lack accurate feedback mechanisms for real-time monitoring, verification, and adjustment of application rates. There is a pressing need for further experiments and research to develop practical solutions that ensure accuracy and effectiveness in feedback systems.

e) VRFA ensure Environmental protection by preventing the wasteful over application of fertilizer and reducing machinery use in the field.

However, further research is necessary to enhance the effectiveness of variable-rate fertilizer applicators, especially through the collaborative efforts of various key areas within precision agriculture research. Consider the integration of prescription maps with real-time soil and plant status data during the sensing process, which has the potential to yield even greater cost savings and precision. By combining these three elements, a more efficient model could be developed for accurately estimating the optimal amount of fertilizer to apply.

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