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Potential of using statistical quality control in agriculture 4.0

Potencial de uso do controle estatístico de qualidade na agricultura 4.0

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ABSTRACT - Agriculture 4.0 involves the incorporation of information and communication technologies into machines, equipment, and sensors for use in agricultural production systems. It aims to ease decision-making in agricultural processes. Statistical Quality Control (SQC) is a statistical method with several techniques and tools used to analyze the variability. These tools can be used to provide important information for decision making, including for mechanized agricultural operations. This paper aimed to characterize the worldwide scientific literature on Statistical Process Control use in mechanized agricultural processes, demonstrating its potential to be incorporated into Agriculture 4.0. Our research involved a bibliometric survey on Scopus and Academic Google databases. The analyzed studies allowed us to infer that SQC tools may improve understanding of mechanized operations and be used in Agriculture 4.0. Such features can also streamline and enhance decision making, converting big data into useful information.

Key words: Statistical process control. Digital agriculture. Quality tools. Quality indicators.

RESUMO - A Agricultura 4.0 envolve a incorporação de tecnologias de informação e comunicação em máquinas, equipamentos e sensores para uso em sistemas de produção agrícola e tem como principal objetivo, facilitar a tomada de decisões em processos agrícolas. O Controle Estatístico de Qualidade (CEQ) é um método estatístico que utiliza várias técnicas e ferramentas para analisar a variabilidade dos dados, ferramentas estas que podem ser utilizadas para fornecer informações importantes para a tomada de decisões, inclusive para operações agrícolas mecanizadas. Este trabalho teve como objetivo buscar na literatura científica mundial o estado da arte na utilização do Controle Estatístico de Qualidade em processos agrícolas mecanizados, demonstrando também o seu potencial para ser incorporado na Agricultura 4.0. Nossa pesquisa envolveu um levantamento bibliométrico nas bases de dados Scopus e Google Acadêmico. Os estudos analisados permitiram inferir que as ferramentas CEQ podem melhorar a compreensão das operações mecanizadas e serem utilizadas na Agricultura 4.0. Esses recursos também podem agilizar e aprimorar a tomada de decisões, de modo a converter dados massivos (big data) em informações úteis e precisas (right data).

Palavras-chave: Controle Estatístico de Processo. Agricultura digital. Ferramentas de qualidade. Indicadores de qualidade.

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INTRODUCTION

Better analyses, waste and failure elimination, and mechanized harvesting improvements are essential to ensure quality standards of mechanized operations (PELOIA; MILAN; ROMANELLI, 2010). Given the requirements in production units, mechanized operations must be carried out in the best possible way, aiming not to compromise process continuity (ALBIERO *et al*., 2010).

Modern agriculture works with management concepts and techniques that promote a wide field of information, which allow producers to seek better strategies and enhance agricultural processes (CASSIA *et al*., 2015).

Statistical Quality Control (SQC) has found wide use in the industrial sector, initially to monitor desirable product characteristics. Over the years and with increasing market competitiveness, it has been increasingly used to detect flaws during the production process and reduce operation variability, as the higher the quality the lower the variability (MONTGOMERY, 2016).

It is completely permissible to use SQC in several crop systems due to its numerous advantages (cost reduction and increased productivity), which can be added to market competitiveness (BONILLA, 1994; MONTGOMERY, 2016). The tool mainly targets to reduce harvesting variability to improve operation quality and stability in the productive sector (TOLEDO *et al*., 2008).

The SQC comprises seven tools, namely: Statistical Process Control (SPC), Histogram, Pareto Diagram, Scatter or Correlation Graph, Flowchart, Check Sheet, and Cause and Effect Diagram (MONTGOMERY, 2016) (Figure 1). Among the quality tools of SQC, the use of SPC stands out, with control charts being applied to monitor how the object of analysis is distributed. All those tools have already been widely used in industrial processes. However, despite the high potential applicability, their use in agricultural processes is still quite incipient, especially in the context of Agriculture 4.0 (SILVA; VOLTARELLI; CASSIA, 2015).

Regarding mechanized agricultural processes, control charts are undoubtedly the most used in Brazilian research (CASSIA *et al*., 2013; CHIODEROLLI *et al*., 2012; MILAN; FERNANDES, 2002; SANTINATO *et al*., 2014; TOLEDO; SILVA; FURLANI, 2013) among others. These control charts can monitor processes and detect possible causes of poor operation quality. The closer the control limits are to the process averages, the lower the operation variability (Figure 2-a). Conversely, out-of-control points indicate greater variability and instability (Figure 2-b), which can directly affect the quality of results and increase uncertainty. When instability is detected in the process, it will affect the quality of results, and such fluctuations cause an increase in measurement uncertainty (ROCHA *et al*., 2017).

SQC has become widely used in different fields of agriculture, mainly in mechanized areas, with emphasis on mechanized harvesting, precision agriculture, remote sensing, application technology, among others. Therefore, this paper proposes to present and discuss available information on SQC use in agriculture. We searched the relevant literature using English terms combined in a tested search string in two publication databases (Scopus and Google scholar).

Below, we present the main studies found in the bibliography reporting the use of SQC tools in agriculture, seeking to establish a connection with their potential for Agriculture 4.0. As most of the articles found are on mechanized harvesting, our review began with this theme, followed by SQC use in sowing, planting, soil tillage, fertilization, spraying, and irrigation operations. The review ends with a discussion on its potential use in Agriculture 4.0.

Mechanized Harvesting

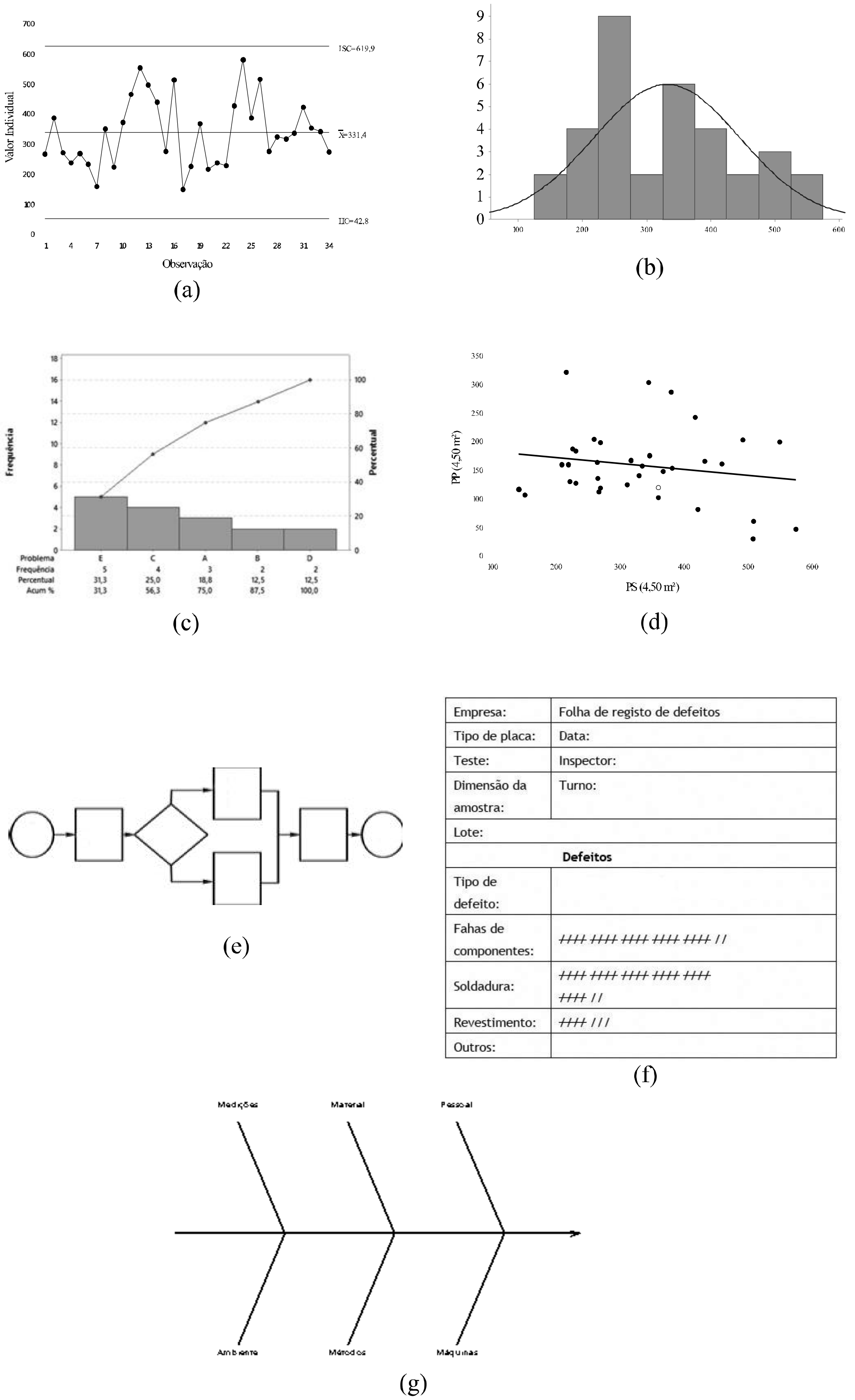
Currently, harvesting operation has been real-time monitored, which makes it easy to monitor the performance of combine harvesters and other machinery items (CHIODEROLLI *et al*., 2012; COMPAGNON *et al*., 2012).

According to Coelho *et al.* (2013), during harvesting, yield maps are generated by harvesters, which allows detecting variability and determining factors affecting the quality of the activity. In practice, farmers have started considering yield variations in cultivation areas to improve harvesting performance and hence profitability (BERNARDI; INAMASU, 2014).

Most of the studies reporting the use of statistical quality control (SQC) in agricultural operations concentrate on mechanized harvesting. Several authors have used SQC to evaluate quality indicators in mechanized harvesting, and the main tool used is individual value control charts (I), alone or in conjunction with moving range control charts (I-MR). Borba *et al. (*2018), used individual charts to analyze effective and operational field capacities, digging and management efficiencies, and maneuvering and machine downtimes, as well as operator personal needs and in-track displacement, seeking to determine which field shape can provide operational efficiency with less variability in peanut mechanized harvesting.

Some authors believe that harvest losses are a good quality indicator of the process. Silva *et al. (*2013),

Figure 1 - Examples of quality tools: a) control charts (Statistical Process Control); b) histogram, c) Pareto Diagram, d) scatter or correlation graph; e) Flowchart; f) check sheet; g) cause and effect diagram



(a)

(b)

(c)

(d)

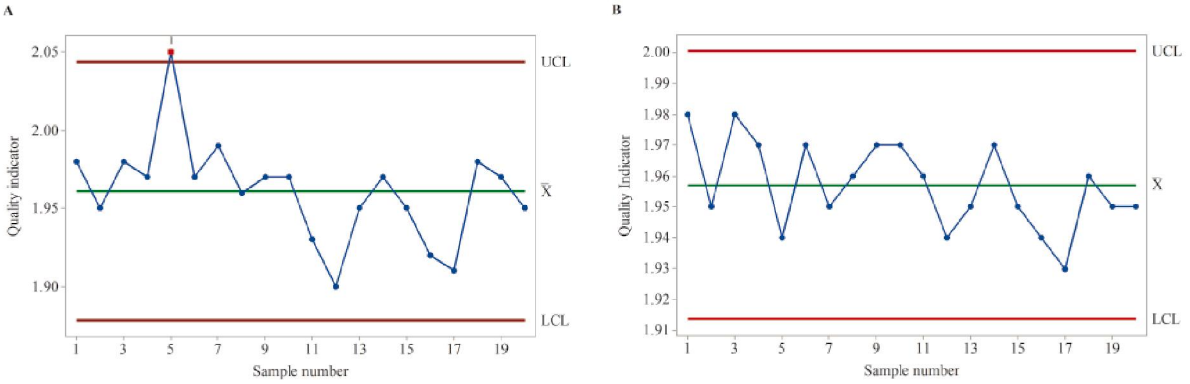
(e)

Empresa:	Folha de registo de defeitos
Tipo de placa:	Data:
Teste:	Inspector:
Dimensão da amostra:	Turno:
Lote:	
Defeitos	
Tipo de defeito:	
Fahas de componentes:	~~////~~ ~~////~~ ~~////~~ ~~////~~ ~~////~~ //
Soldadura:	~~////~~ ~~////~~ ~~////~~ ~~////~~ ~~////~~ ~~////~~ //
Revestimento:	~~////~~ ///
Outros:	

(f)

(g)

Figure 2 - Examples of control chart: a) unstable process; b) stable process



evaluated mechanized harvesting quality of common beans under no- and conventional tillage and found that total loss variability was similar among treatments and remained under control in both systems. When quantifying soil and plant losses in cotton mechanized harvest, Silva *et al. (*2007), observed that the process was not within the quality standards for crop losses. The authors, therefore, suggested that the operation be revised since losses were well above expectations, which demonstrates low harvesting efficiency, jeopardizing final profit.

Compagnon *et al. (*2012), compared loss rates of soybeans on the field with readings of harvester's loss monitor from different periods of the day. Through control charts, they found that the losses obtained by the sensor and field measurements were more similar at nighttime.

Cassia *et al. (*2015), observed that harvester's operational parameters influence soybean losses in mechanical harvesting. They concluded that all the evaluated quality indicators, both quantitatively and qualitatively, were within the limits of statistical control, which attested the quality and stability of mechanized soybean harvesting operation.

According to Menezes *et al.* (2018), harvesting quality is related to decreased losses, which may be affected by the used combine header and harvesting speed. The authors assessed the quality of soybean mechanical harvesting using harvesters with different combine headers and travel speeds via statistical process control (SPC), with I-MR control charts for the indicators: combine header, internal, total, and cutting height losses. The authors concluded that the use of draper header and travel speed had little effect on process quality.

Other authors have also evaluated soybean mechanized harvesting using I-MR control charts for the following quality indicators: crop losses and residue cover distribution (TOLEDO *et al.*, 2008); grain water content, pod number per plant; first-pod insertion height; plant height; crop yield; straw distribution and harvester's operational characteristics (CHIODEROLLI *et al.*, 2012); cutting losses, internal mechanism and total losses, seed water content, straw distribution and yield (LOUREIRO JÚNIOR *et al.*, 2014); harvesting efficiency and soybean losses (PAIXÃO *et al.*, 2016); concave opening, cylinder and engine speeds (PAIXÃO *et al.*, 2017a); grain temperature, water content, concave opening, cylinder rotation, mechanical damage and electrical conductivity (PAIXÃO *et al.*, 2017b).

Evaluating mechanized harvesting of industrial tomatoes using SPC with I-MR control charts, (CUNHA *et al.*, 2014) found that higher rotations of the separation roller increased system losses, which were outside the limits of control and acceptable loss standards for the crop.

Santos *et al.* (2019), evaluated the use of the autopilot in peanut harvesting (digging) by I-MR control charts and observed no differences in total losses between operations with autopilot (AG) and manual guidance (MG). When using autopilot, the digging process quality showed greater variability in losses.

Still, in studies on peanuts, Alves *et al.* (2020), concluded that the highest losses in mechanized harvesting occur below the soil at the time of digging (invisible losses), when the authors found points outside the control limit of I-MR charts, thus characterizing the process as unstable under SPC monitoring.

When analyzing the quality of mechanized sugarcane harvesting using five basal cutting knives, Toledo; Silva and Furlani (2013) observed that flat and serrated blades, as well as normal and inclined discs, present higher process quality and stability concerning the level of damage to knuckles in the control charts. The authors used brainstorming, specification limits, I-MR control charts, histogram, and capability analysis as tools to evaluate quality indicators such as damage levels and cutting heights.

Noronha *et al.* (2011), used I-MR control charts to assess quantitative losses due to changes in mechanized harvesting of sugarcane through SPC. They observed that, for total losses, the process showed out-of-control points during the day and under-control ones during the night. However, the greatest variability of total losses was observed during the night. According to the authors, these results indicate that nocturnal harvest of sugarcane should be more effectively controlled. In addition to harvest losses, cutting heights and ratoon damages were used as indicators.

Bernache *et al.* (2020), used attribute control and individual control charts to assess the quality of basal cutting by correlating ratoon damage and loss indexes with sugarcane regrowth effects. They evaluated the parameters of plant height and position, damage and loss indexes, and stem length every 30 min. Sugarcane regrowth was analyzed by counting the number of tillers and measuring plant height and stem diameter. The authors considered the harvesting out of control for the parameters cutting height, number of tillers, plant height, and stem diameter, but under control for damage and loss indexes, and plant high and position.

Another study by (PAIXÃO *et al.*, 2020) aimed to evaluate losses in sugarcane under mechanized harvesting by estimating losses of stump, loose piece + fixed piece, whole sugarcane, fragment, and total losses as quality indicators in an individual control chart. The authors concluded that sugarcane mechanized harvesting can be considered an operation that can be controlled. These results are like those obtained by Silva *et al.* (2008), and Noronha *et al.* (2011), who also used losses in sugarcane mechanized harvesting as indicators of the quality of harvesting process in individual value charts and I-MR charts, respectively.

Voltarelli *et al.* (2015), aimed to compare three SPC tools (individual values, moving average, and exponentially weighted moving average control charts) applied to losses in sugarcane mechanical harvesting to determine the best control chart template for such quality indicator. They stated the control chart of individual values as the best for monitoring sugarcane mechanical harvesting losses, as its results are easier to interpret than in comparison to the others.

Soares *et al.* (2019), analyzed mechanical harvesting quality for industrial tomatoes by Exponentially Weighted Moving Average (EWMA) control chart. They assessed the following indicators: ripe, discolored, green, and total fruit losses in the soil and in the branch, as well as total fruit losses. The authors concluded that harvesting quality was influenced by random causes in most of the operation time. Therefore, monitoring of the entire harvesting operation must be constant since non-random factors can cause failed operations with high variability, which requires immediate intervention to avoid major fruit losses.

Paixão *et al.* (2019a), also used the EWMA control charts to evaluate soybean mechanical harvesting times, movements, and quality in plots with different shapes. They monitored harvester performance using the following quality indicators: forward speed, engine and cylinder rotations, and concave opening, as well as losses on the platform, internal mechanisms, and total losses. All these indicators were within the limits of statistical control, which characterizes harvesting quality and reliability. In another study, Paixão *et al.* (2019a), used field capacity, harvesting efficiency, and grain losses as quality indicators by SPC using CUSUM-type charts. The authors noted that, if compared to others, rectangular plots had greater management and harvesting efficiencies, while trapezoidal-shaped ones facilitated maneuvers. Overall, the rectangular plot had the best harvesting quality. The authors also concluded that the CUSUM control chart was effective in preventing quality instability and maintenance.

To ascertain basal cutting knife wear of two sugarcane harvester models through I-MR control charts, Paixão *et al.* (2019b), measured thickness increases and width losses. The harvester model with circular knives (racket knives) had lower variability and stability in cutting width, whereas that with conventional knives had more wear in width but less variability in cutting wire thickness.

Peloia; Milan and Romanelli (2010) assessed whether sugarcane mechanized harvesting can supply the quality requirements for the crushing process regarding billet length. The authors analyzed billet cutting by two tools: control charts and studies of capability. Variability was higher in burnt than in green sugarcane. Moreover, none of the harvesters could cut billets at similar lengths when operating, either in burnt or green harvesting.

Alcântara *et al.* (2017), used individual and moving range control charts (I-MR) evaluate the quality of three mechanical methods of sugarcane harvesting: one semi-mechanical and two mechanical ones (self-performed and outsourced) during three working shifts. As quality indicators, they regarded both mineral and vegetal impurities. An SPC analysis showed that the semi-mechanical technique had the highest variability.

Cassia *et al.* (2013), studied coffee mechanized harvesting using SPC, using coffee load, stripping efficiency, collection efficiency, harvested coffee, and leaf losses as quality indicators in I-MR control charts. The authors claimed that all parameters were under control since no points were out of the upper and lower limits. They also observed great temporal variability in samples, but harvesting process remained within acceptable standards, thus being reliable. Using the same chart types, Tavares (2017) evaluated hourly fuel consumption of a special tractor with six possible settings performing coffee mechanized harvesting. The authors monitored fuel consumption at regular hourly intervals and concluded that a mass-power ratio of 56 kg kW^{-1} with driven FWD should be used to decrease wheel slipping and average hourly fuel consumption while increasing harvesting quality.

To maintain mango quality, fruit processing steps and the average weight of fruit boxes should be monitored. To this end, Araújo; Melo and Leite (2017) performed a case study in a mango packing house to determine how much variability in the average weight of mango boxes could influence the final product. Using control charts of individual values and standard deviations, they concluded that the mapping of a dynamic process, together with quality tools, can help reducing losses and failures in the system, ensuring predictability, standardization, and final product quality.

Voltarelli *et al.* (2018), identified critical quality indicators for mechanized harvesting of sugarcane billets. When necessary, the authors developed a continuous improvement plan using FMEA (Failure Mode and Effect Analysis), after the formation of a quality technical team. They evaluated collected variables through control charts of individual values and process capacity indexes. Thereby, 8 critical quality indicators were found for the billet harvesting process. Among these, cutting height, damage index, non-viable bud percentage, and operating speed have greater importance for the analysis because of the risk priority index and ease of data collection for analysis. The authors also concluded that developing an improvement plan aims to reduce the variability of crop billets, thus enabling harvesting within the required quality standards.

Sowing and planting

Among agricultural activities, sowing requires more attention since proper seed deposition depth and spacing are essential to reach a suitable initial stand. Yet, like any other operation, sowing is prone to variability and has its quality reduced, which could affect further operations. In this sense, monitoring variability through SPC has become a feasible and interesting alternative to ensure sowing quality in several crops. According to some authors, the quality indicators are sowing depth, seed longitudinal distribution, final plant population, and crop yield (ORMOND *et al.*, 2019); longitudinal distribution, percentages of normal, double, and skip spacing, as well as seedling emergence (ARCOVERDE *et al.*, 2017); parallelism between passes of tractor-sower sets (ZERBATO *et al.*, 2017); plant height, first-pod insertion height, pod number per plant, cutting height, straw distribution, and yield (ORMOND *et al.*, 2016).

Melo; Albiero and Monteiro (2013) used EWMA charts to assess the longitudinal distribution of corn seeds as a quality indicator of sowing. They concluded that MMEP charts proved to be an adequate tool to assess the quality of longitudinal distribution during the sowing process.

In Brazil, automatic targeting systems have been the main Precision Agriculture techniques used by farmers in agricultural operations. This is because errors range from 2.5 to 3.8 cm, depending on the used correction method (BAIO; MORATELLI, 2011; SANTOS *et al.*, 2018). The use of autopilot enables aligning sowing with crops and their cultural treatments, reducing the overlap of passes and increasing working hours and operator comfort (OLIVEIRA; MOLIN, 2011), among other benefits. However, positioning by Global Navigation Satellite System (GNSS) is subject to errors, which can affect operation quality.

Based on the above, (SANTOS *et al.*, 2016) monitored the quality of mechanized sowing as a function of parallelism errors at sowing. To this end, they suggested using I-MR control charts and twice the standard deviation to calculate lower and upper limits. The authors also proposed the use of 2σ, which seems to be important since the limits estimated using such a value ensure that 95% of the plotted points are within the region of acceptance (between LSC and LIC). In a subsequent study on peanut sowing, (SANTOS *et al.*, 2017) measured and monitored three types of positioning errors through control charts (I-MR) with 2σ. The control charts showed that using an RTX signal, parallelism errors between consecutive passes of the mechanized set were within acceptable limits.

Adding specification control limits (upper and lower; USL and LSL) is one of the advantages of control charts in monitoring processes, mainly for parallelism errors. Specification control limits are values to be reached while monitoring a process, that is, the acceptable positioning errors, upwards or downwards, depending on the used correction method. Parallelism errors will not always remain between USL and LSL, as was observed by (SANTOS *et al.*, 2018), who evaluated two paths for sowing using RTX signal (curved and straight). They found that both showed variability in parallelism values and execution errors greater than the specific control limits. However, these authors also reported that although the values extrapolated USL and LSL, the probability of their occurrence is low compared to errors within control limits, thus making RTX signal a good alternative for farmers.

Santos *et al.* (2016), and Zerbato *et al.* (2019), also used 3σ and I-MR charts and found promising results for peanut sowing using automatic routing with RTK signal. The results of these studies with control charts suggest that alignment in sowing operations tends to reduce harvest losses, increasing operation quality for reducing variability between the control limits, as autopilot is used at least once between sowing and harvest.

Several studies have used SQC to monitor sugarcane planting. Voltarelli *et al.* (2013), used 3σ and I-MR control charts and obtained satisfactory results in planting sugarcane by monitoring the variable parallelism (using RTK signal). However, the authors analyzed parallelism error in sugarcane planting in two shifts and observed that both had points above the control limits, which were attributed to the loss of signal during operation.

Sugarcane mechanized planting has presented difficulties in maintaining quality standards (mills). Voltarelli *et al.* (2014), studied the agronomic performance of a sugarcane mechanized planting during two shifts using I-MR control charts and capability analysis. The authors evaluated the following quality indicators: number of billets m^{-1}, total number of buds m^{-1}, number of viable buds m^{-1}, percentage of viable buds, and seedling consumption (Mg ha^{-1}). They concluded that the operational quality of mechanized planting varied between the day and night shifts. All analyzed quality indicators were deemed incapable (Cp and Pp < 1.33) of meeting the established targets for the day shift, regardless of the process stability. In another study, Voltarelli *et al.* (2016), evaluated the same two operating shifts, on the left and right furrows, using the same quality indicators, and run and control charts as tools. They concluded that combining run and control charts was essential to monitor the process thoroughly, increasing reliability in decision making and thereby improving further operations. Besides, the quality of the operation was affected in both day and night shifts, but it was lower during the night for all quality indicators, mainly on the left furrow.

Compagnon *et al.* (2016), evaluated billet metering quality and uniformity of a sugarcane planter and total damage to buds at two planting speeds (5.0 and 6.5 km h^{-1}) and two conveyor belt rotation speeds (50 and 100%, which corresponds to 45 and 85 rpm, respectively, in the conveyor belt pulley). They used I-MR control charts to evaluate the following quality indicators: number of billets m^{-1}, total buds m^{-1}, viable buds m^{-1} and damaged buds. Their results showed that planter metering mechanism showed a uniform billet metering, with low bud damage. The authors also noticed that the increase in working speed and in conveyor belt rotation speed decreased the number of billets, as well as total and viable buds.

Sugarcane planters must simultaneously perform furrowing, fertiliser application, seedling metering and furrow covering operations. Based on this, Compagnon *et al.* (2016), evaluated such planting steps using as quality indicators: number of billets m^{-1}, total and viable buds m^{-1}, percentage of inviable buds, furrow depth, furrow width, disturbed area, and seedling cover height as a function of different planting speeds and furrow depths. Their results showed that, through I-MR control charts, as planting speed increased disturbed area increased and cover height decreased, while an increase in-furrow depth increased disturbed area, furrow width, furrow depth, and cover height. Furrow opening, seedling metering, cover height, planting depths, and operation speed were uniform during planting.

Soil tillage, fertilization, spraying, and irrigation

Implementing tillage practices focused on soil conservation is a key aspect of modern agriculture. The goal is also to improve cultivation conditions, sustaining or even increasing crop productivity, and maintaining soil and environmental quality standards in a production system (RAIESI; KABIRI, 2016).

There are several management methods so that the soil presents ideal conditions for cultivation. From a conservationist perspective, there is a no-tillage system, wherein rotation crops are used to replace essential nutrients and decompress surface layers biologically and sustainably (DUARTE-JÚNIOR; COELHO, 2008), avoiding excessive soil overturning by tillage implements. There are also minimum tillage methods, which focus on promoting the least possible soil overturning and reducing the number of operations (TAVARES, 2010), still seeking better conditions for crop development. Finally, there are the conventional soil tillage practices, which make use of implements such as harrows and plows, among other tools capable of unpacking the soil to deep layers, besides incorporating organic matter and inputs in-depth (SALES *et al.*, 2016). However, regardless of the soil tillage method chosen by a production unit, it is essential to use tools capable of identifying, differentiating, and qualifying execution and results of the operation performed.

Pre-planting soil management requires that determinant factors on soil tillage quality be achieved so that crops could develop vigorously and homogeneously under conditions to achieve high yields and promote plant or animal health (DORAN; ZEISS, 2000). According to Bünemann *et al.* (2018), soil quality indicators are divided into physical, chemical, and biological. The same authors suggest choosing the main indicators to be evaluated in advance, regarding financial and time issues, as well as to avoid collinearity limitations. This selection of indicators is also addressed by tools of Statistical Quality Control, called "brainstorming," increasing assertiveness through ideas and suggestions from members involved in the process (VOLTARELLI *et al*., 2018).

Assessing soil management for eucalyptus replanting, Gava (2003) used an important quality tool in agricultural operations, the specification of control limits. They were able to detect the best mechanized-set to be used under each soil condition in the hour for the opening of furrows. Similarly; Milan and Fernandes (2002) used SPC tools to assess the quality of chiseling and harrowing operations and, through them, make assertive decisions to improve these processes, using tillage depth as a quality indicator. The authors concluded that the use of histograms, control charts, and specific limits resulted in increments of up to 75% in the quality of indicators used to assess the soil preparation processes.

Mechanized agricultural operations have high variability (OLIVEIRA *et al*., 2020), mainly due to field heterogeneity, which strongly affects the quality of the operation being carried out and of subsequent operations. It was noted by (ORMOND *et al*., 2018), who evaluated the quality and effect of two different soil tillage methods on peanut mechanized harvesting. The authors used I-MR control charts and concluded that SPC tools enabled detecting failures due to the influence of tillage methods on harvesting, which is the last operation performed during a crop cycle.

Mechanized operation variability must be controlled during any and all operations to avoid harming future operations. However, it is most common during furrow operations for further seedling transplanting, when parallelism errors and alignment of mechanized sets can occur. Silva *et al.* (2014), evaluated furrowing and transplanting of coffee seedlings and observed, through I-MR control charts, alignment failures during soil tillage greater than 20 cm. They used as quality indicators: mechanized assembly alignment error, operation speed, and tractor driving wheel slip. Similar results were also observed during soil tillage for transplanting of citrus seedlings (VIDAL *et al*., 2016), wherein mechanized sets did not reach the expected accuracy, with failures during operations observed in I-MR control charts. In this case, the quality indicators used were: tractor driving wheel slip, speed of mechanized sets, GPS-receiver accuracy, and a study of time and motion operations to estimate the efficiency of tillage operations.

A new concept of fertilizer machine that applies fertilizers individually (N, P, and K separately) was evaluated by (CARNEIRO *et al*., 2017a; CARNEIRO *et al*., 2017b) in two studies. In the first one, Carneiro *et al.* (2017a), studied combined operations with and without herbicide application and fertilizer application on each side of the fertilizer machine. The authors used I-MR control charts and fertilizer distribution efficiency as a quality indicator. They quantified the amount of fertilizer applied and concluded that operational quality was better in two distinct operations and that the right side showed the best results, as it reached an amount close to the regulated dosage. In the second study, Carneiro *et al.* (2017b), ascertained the quality of an individual mechanized NPK fertilization in sugarcane ratoon, using I-MR control charts and, as a quality indicator, the amount of NPK fertilizers distributed when applied independently one from the other. The authors concluded that individual application resulted in doses above the recommended for all nutrients due to an adjustment of the helical metering system. Nitrogen (protected urea) showed the greatest variability in distribution, whereas phosphorus (MAP) displayed the highest operating quality due to its lower recommended dose.

Society has been increasingly concerned with chemical use in agricultural processes in recent years (GIL; SINFORT, 2005). Farmers have applied agrochemicals mainly to control diseases, pests, and weeds, following conventional crop protection strategies. On the one hand, one advantage is the control of problems so that crops could reach their potential production. On the other hand, disadvantages are mainly due to limitations of current conventional spraying technologies (PARTEL; CHARAN KAKARLA; AMPATZIDIS, 2019).

In most situations, during chemical control of pests, diseases, and weeds, much importance has been given to phytosanitary products and little attention to application technology (REIS *et al*., 2010). As a consequence, there has been the loss of control efficiency, or even total failure of the process due to overdoses or underdoses, which may lead to loss of production and damage to the environment and human health (CUNHA; RUAS, 2006). Besides knowing the agrochemical to be used, a suitable application method is of paramount importance to ensure that the product reaches its target efficiently, minimizing losses and environmental damages (CUNHA *et al*., 2005). Thus, quality control tools have been widely used (REIS *et al*., 2010; SILVA; CUNHA; NOMELINI, 2016; SUGUISAWA *et al*., 2007), bringing as advantages correction and elimination of waste and failures, cost reduction, and increased productivity. Below we present studies on the use of these tools for aerial spraying, both in perennial crops and annual crops.

Advances in aerial spray application technology have been focused on reducing spray volume, which can cause poor distribution and hence irregular deposition. In this sense, Reis *et al.* (2010), developed a study to evaluate the quality of aerial spraying in soybeans (*Glycine max* L.), using control charts of individual values. They used as quality indicators volumetric median diameter, relative amplitude, and spray coverage. The results found indicated that the middle third of plants presented lower volumetric median diameters, relative amplitudes, and spray coverages compared to the upper third. They also reported lower spray deposition in the lower third. Spray coverage indicators demonstrated that aerial spraying using the evaluated agricultural aircraft was not under SPC, that is, out of the quality standard.

As for spraying in perennial crops, coffee (*Coffea arabica* L.) growers have gone through several challenges, mainly for spray droplet penetration into the inner canopy and spray drift reduction (SILVA; CUNHA; NOMELINI, 2016). The authors reported that coffee plant architecture and its large leaf area index hinder penetration and leaf coverage through spraying. Therefore, they used quality tools (individual control charts) to evaluate spray deposition on coffee leaves and respective loss to the soil by applications using air-blast sprayers, with different spray volumes and drop sizes. Their results indicated that, from a point of view of statistical control, air-blast sprayers present a good quality standard regarding deposition repetition on leaves and on the soil throughout the application, promoting a consistent coverage regardless of droplet sizes and spray volumes.

As for annual crop spraying, we found quality tools being used in wheat (*Triticum sativum* L.). Suguisawa *et al.* (2007), analyzed through quality tools (histograms and individual values control charts) the operational quality of herbicide application in wheat crops, with changes in density and droplet coverage. They noted that the process had irregularities and high variability, thus requiring improvements. However, operation quality was considered reasonable given the characteristics of used products (systemic). The authors made an association among control charts, histogram, and GIS software (Geographic Information System) and inferred that these tools allowed characterization of operational variability, so they can be considered efficient as tools for quality analysis of herbicide spraying.

If done improperly, irrigation may cause several consequences such as drought or excess of moisture to plants, which can increase operating expenses, environmental impact, and nutrient leaching, as well as making the environment favorable for the appearance of pathogens, due to increased soil moisture. However, water deficit impairs plant development leading to the consequent loss of crop yield and increased losses. Therefore, quality tools are needed to monitor crop systems and reduce failures occurring during processes.

Among the studies that used SQC for irrigation quality control, Andrade *et al.* (2017), monitored uniformity coefficients through individual value control charts and process capability index (Cp), evaluating water application uniformity by a micro-sprinkler system. These researches found satisfactory results for the use of control charts. They also observed that an increase in process capability index was directly proportional to distribution uniformity (DU) and Christiansen uniformity (CUC) coefficients.

Using the same analyses, Rocha *et al.* (2017), monitored a drip irrigation system and identified process stability or instability. They could also classify the measurement system as approved or acceptable through those indices. In this case, the authors used EWMA control charts and capability analysis to monitor the quality characteristics of water temperature and dripper flow rates.

SQC tools have also been used for decision making in improvement plans. For example, Chinchilla *et al.* (2018), monitored unstable drip irrigation due to failures such as pipe clogging. Through error identification, they inferred that these tools are useful for monitoring and establishing corrective actions and hence increase the quality of the process. The authors used subgroups of control charts and specification of limits for the quality indicator dripper flow rates.

Hermes *et al.* (2013), measured fertigation uniformity by control charts and capability indexes and classified flow variation coefficients from good to excellent. According to these authors, capability indexes can be used to check fertigation quality, allowing system capability evaluation to maintain tolerable uniformity levels.

Other studies in the field of irrigation that have used SQC deal with water quality monitoring. For Freitas (2015), these tools allowed a water treatment company to establish an improvement plan based on corrective and preventive measures.

Given the above, it is clear how the use of SQC tools have contributed to improving the quality and management of irrigation systems. With them, errors that are made during operation can be identified, aiming at

Figure 3 - Main Statistical Quality Control tools used in agriculture. CC: control charts; I: individual values; I-MR: individual - moving range

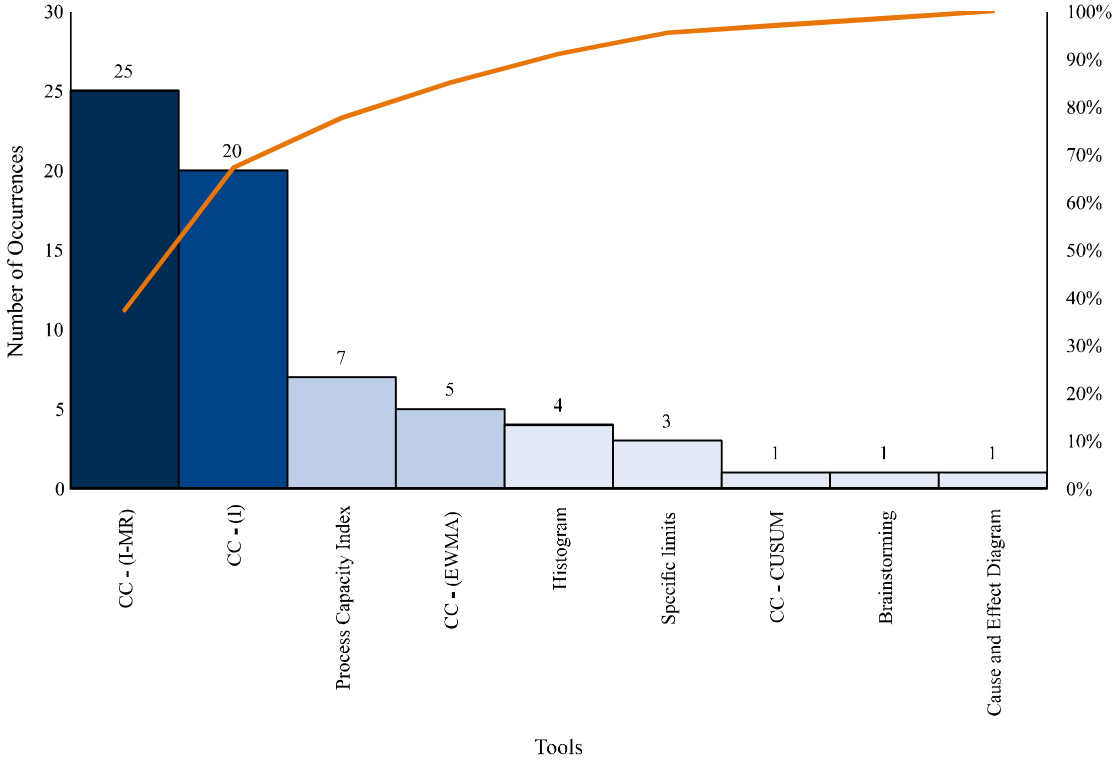


Figure 4 - Main quality indicators used in agriculture studies

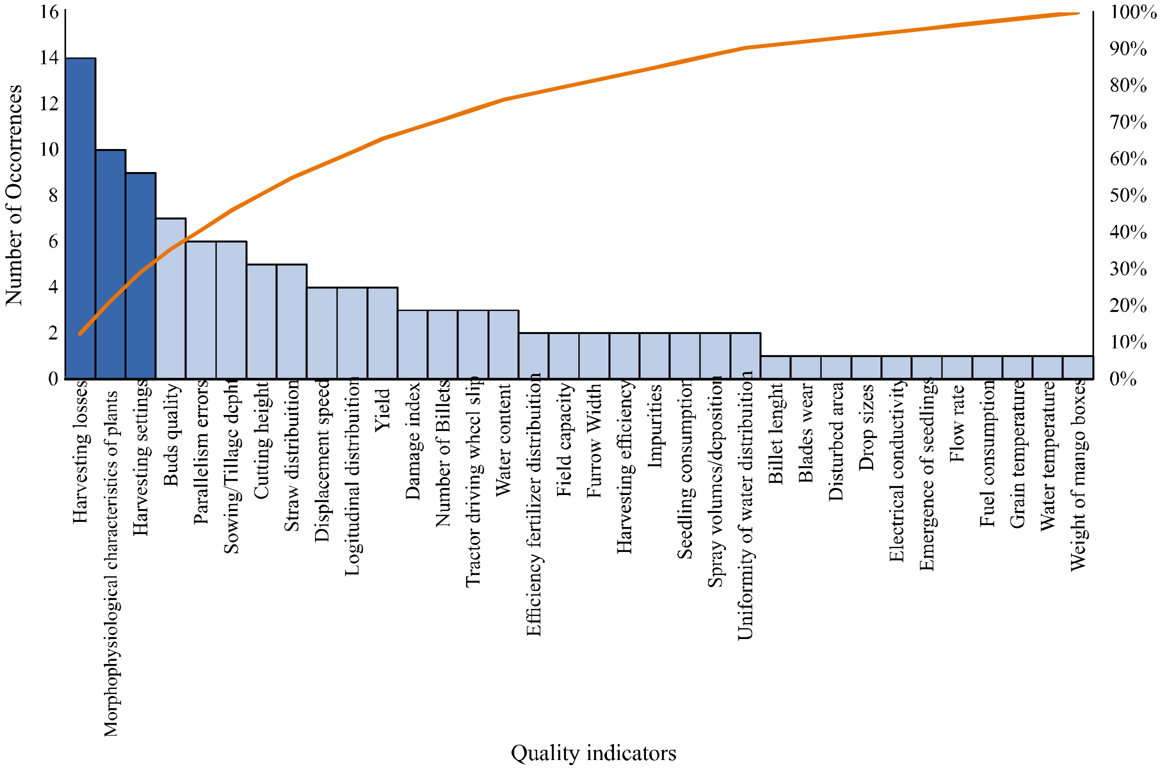
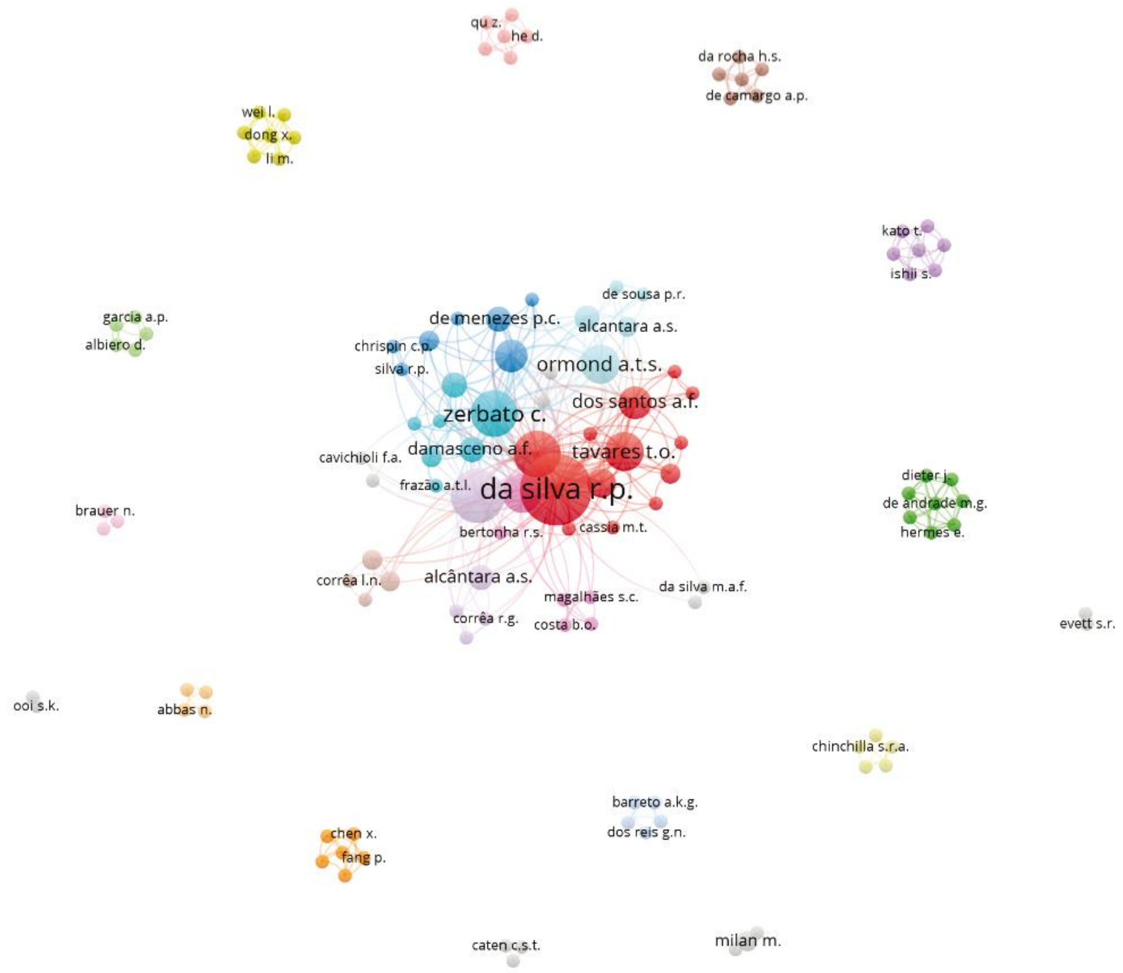


Figure 5 - Map of the network of researchers based on their publications (using keywords such as “Statistical Quality Control” AND “Agric* machinery” OR “agric* mechanization” OR “irrigation”



reducing environmental damages and producer expenses, and concomitantly increasing sustainability through a proper operation use.

Potential use of SQC in Agriculture 4.0

Agriculture digitization, which is referred to in the sector as Agriculture 4.0, has radically transformed agricultural production processes, contributing mainly to management by interpreting past data to make future estimates, promoting increasingly assertive decision-making measures (KLERKX; JAKKU; LABARTHE, 2019). Operation quality analysis depends on its correct monitoring, mainly in its initial steps such as in data collection for process interpretation, which requires care and quality to be assertive (WOLFERT *et al.*, 2017). Quality control can be used for evaluation of processes and products and is important to detect and reduce variability.

Figure 3 shows the main tools used in the studies researched in this review. One can verify a predominance in the use of I-MR control charts (individual – moving range), followed by individual value charts (I). Following, among the most used are process capacity analysis, EWMA control charts, histograms, and finally specification limits.

Eleven of the 34 quality indicators found in the surveyed studies represent 65% of the most used for quality evaluation. Figure 4 highlights that harvest losses are the most used variables for assessing mechanized harvest quality, followed by indicators related to harvester regulation (3rd position in general). Overall, plant morphophysiological characteristics appear in second place since they encompass several other variables such as plant height, insertion height, stem diameter, etc. Also, other quality indicators that worth mentioning are bud quality, parallelism error, sowing/tillage depth, cutting height, straw distribution, displacement speed, longitudinal distribution, and crop yield.

Figure 5 shows that publications in the Scopus database belong mainly to some researchers in the state of São Paulo (Brazil), in particular those from the State University of São Paulo (UNESP), Campus of Jaboticabal. However, such studies have been increasingly performed in other regions of Brazil and abroad.

Although the results of the above-mentioned studies are promising, quality tools can be difficult to use under field conditions. Moreover, together with the lack of in-depth knowledge about processes, procedures for digitizing services in the field should be well understood, as they are not commonly done in most farms. However, advances in digital technologies and use of sensors can facilitate automatic digitization of processes, and then quality tools can be easily implemented to perform fast and accurate decision makings.

In recent years, robotic technologies have been employed, and there are reports that these could reduce product waste, improving sustainability and reducing environmental impact (BERENSTEIN; EDAN, 2017).

Another interesting application is the use of sensors, satellites, or unmanned aerial vehicles (UAVs) to obtain information that establishes relationships with environmental and agronomic factors. This allows the development of prediction and forecasting systems based on this information (GARZA *et al.*, 2020) and to identify problems in the field in real-time (PEERBHAY; GERMISHUIZEN; ISMAIL, 2019). In this way, it becomes possible to intervene in a targeted manner where the problem is occurring, saving resources and carrying out more effective interventions, with a positive impact on product quality. These applications have great potential for digital agriculture and will therefore be good for both companies and farms, as well as for sustainable development (ADNAN *et al.*, 2018).

According to data by Borghi *et al.* (2016), on producers' expectations towards adopting variable-rate seeding, we believe that control charts will be a promising tool in the monitoring of agricultural operations. Accordingly, several studies in the literature have already used quality management, mainly in mechanized sowing and harvesting, and in post-processing (data measured after the operation). Then, plotting points on the sowing and harvesting monitor during the process can contribute to the precision and quality of operations at variable rates in real-time. That way, the operator himself identifies the problem and corrects it before resuming the process.

Although extremely important, no studies have evaluated Statistical Quality Control and Digital Agriculture jointly. Due to technological advances, a large volume of data (big data) from sensors has been installed at different types of platforms (machines, weather station, satellite, UAV - Unmanned Aerial Vehicle, etc.). Thus, most accurate statistical analyses such as the use of SQC are required to enable the transformation of big data into meaningful information.

More accurate statistical analyses like as SQC are required for transformation of big data into meaningful information (right data). In this sense, SQC becomes a great tool since it allows system management and impose desired limits and/or standards. It also has great potential to be implemented in agriculture 4.0. In this process, work patterns are set so that machines perform it, seeking efficiency and effectiveness. This is based on monitoring by sensors, which are capable of storing data for possible future.

CONCLUSIONS

Due to the excellent results obtained by several authors, the use of Statistical Quality Control clearly allows a better understanding of mechanized operations. As quality tools have proven to be efficient for assessing and interpreting variability in several indicators, they have great potential for use in Agriculture 4.0 and can contribute to decision-making effectively and quickly, allowing the transformation of big data into meaningful information.

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