International Journal of Statistics and Applied Mathematics 2024; 9(6): 115-120

International Journal of Statistics and Applied Mathematics

ISSN: 2456-1452
Maths 2024; 9(6): 115-120

https://www.mathsjournal.com
Received: 11-10-2024
Accepted: 19-11-2024

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An optimal study on process control mechanics to measure the pH level in hydroponics system

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DOI: https://doi.org/10.22271/maths.2024.v9.i6b.1905

Abstract
This article presents the construction and design of statistical process control mechanisms in hydroponics system. This system is soilless culture of plants such as temperature, water limit, pH level and nutrients substance for the plants. Its helps to increase the productivity over a series of continuous monitoring system an alternative method of cultivation in a smaller areas. Here an attempt is made to reduce the farmer's effort without human intervention to reduce loss, increase productivity. An important methodology of control chart for attributes is proposed to detect changes in production processes, through statistical level of confidence. The experiment were gathered with a suitable dataset by applying Cumulative Sum Control (CUSUM) chart was employed to study the proposed dataset to monitor and detect any deviations from the pH range and ensure that plant growth remains consistent and unaffected by potential fluctuations in the hydroponic environment in water spinach. The result are provided with numerical illustrations towards highlighting that even though a wider range of pH levels was performed well in the plant height on weekly basis of water spinach as a parameter, which indicate that the process is stable and consistent. Also, statistical analyses were performed using the Minitab 22 software are provided with suitable applications.

Keywords: SPC, hydroponics, water spinach, CUSUM control chart, PH level, plant height

Introduction
By 2050, the human population is expected to reach 8.9 billion (USAID 2004), and a major challenge for the increased population will be maintaining the supply of fresh produce to ensure nutrient rich diets. Urbanization, industrial growth, and climate change are reducing cultivable land, driving the adoption of hydroponics. Hydroponic or soilless production could be an important solution to this problem because of its higher yields and more nutritious food when compared to soil production. Hydroponics can be defined as a technique of growing non-aquatic plants without soil in a nutrient solution with or without soilless substrate. Maintaining an adequate nutrient solution and pH level are often cited as major obstacles to hydroponic production. Frick and Mitchell (1993) indicated that pH of a hydroponic nutrient solution fluctuates because of the unbalanced anion and cation exchange reaction with roots and there is no buffering capacity in hydroponics as in soil.

Modern agriculture works with management concepts and techniques that promote a wide field of information, which allow producers to seek better strategies and enhance agriculture processes. Statistical Process Control (SPC) has become widely used in different fields of agriculture, mechanized areas, with emphasis on mechanized harvesting, precision agriculture, remote sensing, application technology, among others. Most of the studies reporting the use of SPC in agriculture was effective in quantifying and monitoring the processes and also contribute to decision-making effectively and quickly, allowing the transformation of big data into meaningful information.

Statistical Process Control is a methodology used for monitoring and controlling processes to ensure they operate at their full potential. In hydroponics, a highly controlled agricultural system, SPC serves as a critical tool for maintaining optimal growing conditions for plants. SPC started in the manufacturing industries in the 1920s, but there are now abundant applications in health care and epidemiology.

SPC is the application of statistical methods to the monitoring of a process to ensure that it operates at its full potential to produce conforming product. Under SPC, a process behaves predictably to produce as much conforming product as possible with the least possible waste. While SPC has been applied most frequently to controlling manufacturing lines, it applies equally well to any process with a measurable output. Key tools in SPC are control charts, a focus on continuous improvement, and designed experiments. The control chart is an on-line process -monitoring technique widely used and it's may also be used to estimate the parameters of a production process, and, through this information, to determine process capability. The control chart may also provide information useful in improving the process. Control chart may not be possible to completely eliminate variability, but the control chart is an effective tool in reducing variability as much as possible. The control chart was invented by Walter A.Shewhart working for Bell labs in the 1920s.Shewhart's chart are effective for detecting large changes in process parameters; however Shewhart chart may take a long time to detect a small persistent shift in the process parameter. The ability to detect smaller parameter shifts can be improved by using a chart based on a statistic that corporate information from past samples in addition to current samples. A major disadvantage of a shewhart control chart is that it uses only the information about the process contained in the last sample observation and it ignores any information given by the entire sequence of points. Two very effective alternatives to the shewhart control chart may be used when small process shifts are of interest: the CUSUM control chart, and the exponentially weighted moving average (EWMA) control chart. This study choose the CUSUM control chart developed by Page (1954). This chart plots the cumulative sums of deviations of the sample values of a quality characteristic from a target value against time. It is noted that Shewhart's control chart for mean is very effective if the magnitude of the shift is 1.5 -sigma or larger (Montgomery 2001) [7]. Some authors namely Duncan (1974), Lucas (1976), Hawkins (1981), Lucas and Saccucci (1982a, 1990) stated that the CUSUM control chart is much more efficient than the usual $\bar{X}$ control chart for detecting smaller variations in the average. Paixao *et al*. (2019a), used the CUSUM control chart to evaluate mechanical harvesting efficiencies. It's was effective in preventing quality instability and maintenance. Sheng-Shu and Fong-Jung (2013) [11] reported that the CUSUM control chart performed better than the EWMA control chart in monitoring the failure mechanism of wafer production quality control. Benoit and Pierre detected the persistent changes in the mean and variance in the state of marine ecosystems, while using indicators of North Sea cod from the International Bottom Trawl Survey (2009**)**. Their results showed that the CUSUM control chart is suitable for detecting small, persistent changes. There are two ways to represent a CUSUM, the tabular or algorithmic CUSUM and the V- mask CUSUM. Of these two forms the tabular form of the CUSUM is practiced more. So we consider the construction and use of the tabular CUSUM in this paper.

This study focus on using cumulative sum control chart to testing the water spinach will grow in hydroponic system is stable using varying pH levels. A wide variety of plants can be grown using a hydroponic system. Plants such as rice, corn, strawberries, beets, cabbage, cauliflower, basil, and many more are able to be grown in hydroponics. Water spinach (Ipomoea aquatica) were selected for an experiment because of the relatively quick growing time. Water spinach (Ipomoea aquatica) is a plant that is included in the type of vegetables and is widely cultivated as food. Water spinach is a plant that is easy to cultivate and can be done in the midst of limited land using the hydroponic method (Nanda and Khozin (2022)) [8]. According to Mulasari (2018) hydroponic is a business of cultivating plants without using soil media but using nutrient mineral solutions or using other media such as coconut fiber, broken brick, sawdust and others. Water spinach (Ipomoea aquatica Forssk) contains adequate quantities of vitamins, amino acids (Rao *et al*. (1990)) and antioxidant components. It grows in the wild and is cultivated throughout Asian countries, such as China, Malaysia, Singapore, Sri Lanka, and Thailand, as a common ingredient utilized in many standard dishes. Water spinach has been used as folk medicine against different diseases including diabetes (Garcia (1955), Jayaweera (1982), Villasenor *et al*. (1998)) liver malfunction (Badruzzaman and Husain (1992)) and constipation. It is also supposed to possess hypoglycemic effects (Malalavidhane *et al*, (2000, 2003)) and inhibit prostaglandin synthesis.

Fig 1: Water spinach (Ipomoea aquatica)

2. Order Statistics

Suppose we have a set of random variables $X_1, X_2, \ldots, X_n$, which are independent and identically distributed (i.i.d). By independence, we mean that the value taken by a random variable is not influenced by the values taken by other random variables. By identical distribution, we mean that the probability density function (PDF) (or equivalently, the Cumulative distribution function, CDF) for the random variables is the same. The k^{th} order statistic for this set of random variables is defined as the k^{th} smallest value of the sample.

Let us consider 5 random variables X_1, X_2, X_3, X_4 and X_5. We'll observe a random realization/outcome from the distribution of each of these random variables. Suppose we get the following values:

The k^{th} order statistic for this experiment is the k^{th} smallest value from the set{4, 2, 7, 11, 5}.

$$X_1 \rightarrow 4,\ X_2 \rightarrow 2,\ X_3 \rightarrow 7,\ X_4 \rightarrow 11,\ X_5 \rightarrow 5$$

So, the 1^{st} order statistic is 2 (smallest value), the 2^{nd} order statistic is 4 (next smallest), and so on. The 5^{th} order statistic is the fifth smallest value (the largest value), which is 11. We repeat this process many times i.e., we draw samples from the distribution of each of these i.i.d random variables, & find the k^{th} smallest value for each set of observations. The probability distribution of these values gives the distribution of the k^{th} order statistics.

In general, if we arrange random variables $X_1, X_2, \ldots, X_n$ in ascending order, then the k^{th} order statistic is shown as:

$$X_{(1)} \leq X_{(2)} \leq \ldots \leq X_{(k)} \leq \ldots\ldots \leq X_{(n)}$$

The general notation of the k^{th} order statistic is $X_{(k)}$. Note $X_{(k)}$ is different from X_k. X_k is the k^{th} random variable from our set, whereas $X_{(k)}$ is the k^{th} order statistic from our set. $X_{(k)}$ takes the value of X_k if X_k is the k^{th} random variable when the realizations are arranged in ascending order. The 1^{st} order statistic $X_{(1)}$ is the set of the minimum values from the realization of the set of 'n' random variables. The n^{th} order statistic $X_{(n)}$ is the set of the maximum values(nth minimum values) from the realization of the set of 'n' random variables. They can be expressed as:

$X_{(1)}=\min\{ X_1, X_2,\ldots\ldots X_n\}$

$X_{(2)}=\min(\{X_1, X_2,\ldots\ldots X_n\} -\{X_{(1)}\})$

$X_{(k)} = \min(\{X_1, X_2,\ldots\ldots X_n\} -\{X_{(1)}, X_{(2)},\ldots\ldots X_{(k-1)}\})$

$X_{(n)} = \min (\{X_1, X_2,\ldots\ldots X_n\} -\{X_{(1)}, X_{(2)},\ldots\ldots,X_{(n-1)}\})=\max\{X_1, X_2,\ldots\ldots X_n\}$.

2.1 Cumulative Sum Control Chart

The CUSUM chart was first proposed by Page (1954) as a supplement to the Shewhart chart. As the name indicates, the CUSUM chart is based on cumulative sum of sample observations, using both previous and current information in process to check process status. Owing to the fact that on-line measurement and distributed computing systems become a norm in today's SPC applications, the application of CUSUM chart is becoming popular. For example, the CUSUM chart is widely used in the chemical and process industries. In these applications, the CUSUM charts are able to detect process shifts in both mean and variance, and to identify the point in time when the process shift occurs (Khoo 2005, Wu and Wang 2007). The quality statistic C_t for the t^{th} sample in the original CUSUM chart (Hawkins and Olwell 1998) is updated as follows:

$C_t = \sum_{i=1}^{t} (x_i - \mu_0)$. (2.1)

Equation above can be written in a recursive form:

$C_0=0$

$C_t = C_{t-1} + (x_t - \mu_0)$ (2.2)

If the standard value $z_t (= (x_t - \mu_0 / \sigma_0)$ of the quality characteristic x_t is used instead,

Equation (2.1) is transformed into:

$C_t = \sum_{j=1}^{t} z_t$ (2.3)

Or in a corresponding recursion form

$C_0=0$

$C_t = C_{t-1} + z_t$. (2.4)

The plotting of the CUSUM control chart is similar to that of the Shewhart chart, except that the plotted statistic is C_t for the t^{th} sample. When a plotted point C_t exceeds the control limit, the process is thought to be out-of-control. The design of the CUSUM charts has attracted a lot of research effort in recent years.

2.2 The Tabular CUSUM for Monitoring the Process Mean: Let x_i be the i^{th} observation on the process. When the process is in control, x_i has normal distribution with mean μ_0 and standard deviation σ (known or estimable). Sometimes, μ_0 is taken to be the target value for the quality characteristic X. If the process drifts or shifts off this target value, CUSUM will signal, and an adjustment is made to some manipulatable variable to bring the process back on target. The tabular CUSUM works by accumulating the deviations from μ_0 that are above target with one statistic C^+ and that are below target with another statistic C^-. The statistics C^+ and C^- are called one sided upper and lower cusum respectively.
They are calculated as

$C_t^+ = \max(0, x_t - (\mu_0 + K) + C_{t-1}^+)$ (2.5)

$C_t^- = \max(0, (\mu_0 - K) - x_t + C_{t-1}^-)$ (2.6)

where the starting values are $C_0^+ = C_0^- = 0$

The value of k is called the reference or allowable value and it is often chosen about halfway between the target μ_0 and the shift of mean μ_1 which one is interested in detecting.

Thus, $K = \frac{1}{2}. |\mu_1 - \mu_0|$

The CUSUM values C_t^+ and C_t^- accumulate deviation from the target value μ_0 that are greater than K. If either of the two exceeds the decision interval H, the process is said to be out of control. A reasonable value of H is five times the process standard deviation σ. Here H = h * σ and K = k * σ are the parameters of the CUSUM chart (Montgomery 2001) [7]. The action taken following an out-of-control signal on a CUSUM control scheme is identical to that with any control chart; one should search for the assignable cause, take any corrective action required, and then reinitialize the CUSUM at zero. The CUSUM is particularly helpful in determining when the assignable cause has occurred; just count backward from the out -of-control signal to the time period when the CUSUM lifted above zero to find the first period following the process shift. The counters N^+ and N^- are used in this capacity. In certain situations where an adjustment to some manipulatable variable is required in order to bring the process back to the target value μ_0, it may be helpful to have an estimate of the new process mean following the shift. This can be computed from

$\hat{\mu} = \mu_0 + K + \frac{C_i^+}{N^+}$, if $C_i^+ > H$

$\mu_0 - K - \frac{C_t^+}{N^-}$, if $C_i^- > H$ (2.7)

The quantities N^+ and N^- indicate the number of consecutive periods that the CUSUMS C_t^+ and C_t^- have been nonzero. The tabular CUSUM will signal when either C_t^+ or C_t^- exceeds the control limits.

2.3 The Fusion of Order Statistics in CUSUM

The combination of order statistics with the tabular CUSUM in control chart is inevitable which has developed many sophisticated and innovative framework towards process monitoring and control the variability. Order statistics provide the dataset a static, ordered form may improves production and provides an less defective. Order statistics form the structural backbone of this integration by providing a rigorous mechanism for arranging and summarizing datasets. Given a sample X_1, X_2, …, X_n order statistics rearrange the data as $X_{(1)} \leq X_{(2)} \leq \ldots \leq X_{(k)} \leq \ldots \leq X_{(n)}$ where $X_{(i)}$ represents the i^{th} smallest value. The mean, computed as $\bar{X}$ offers a comprehensive measure of central tendency, reflecting the dataset's overall behaviour. Unlike robust metrics such as the median, the mean incorporates all data points, making it sensitive to subtle shifts and suitable for processes where uniformity in data characteristics is expected. This sensitivity is crucial in scenarios where gradual deviations, often overshadowed by noise, must be identified to maintain process integrity.

The static nature of order statistics, while invaluable for summarizing datasets, and provide the ability to track dynamic changes over time. The tabular CUSUM control chart bridges this gap by continuously monitoring process performance relative to a target value, $\mu_0$which in this framework is derived from the mean calculated through order statistics. The tabular CUSUM accumulates deviations from μ_0 over successive observations, maintaining separate upward C_t^+ and downward C_t^- cumulative sums: The mathematical formulation of the CUSUM:

$$C_t^+ = \max(0, x_t - (\mu_0 + K) + C_{t-1}^+)$$

$$C_t^- = \max(0, (\mu_0 - K) - x_t + C_{t-1}^-)$$

Where the starting values are $C_0^+ = C_0^- = 0$. Where k is the reference value that balances detection sensitivity and false alarm rates, and H is the decision interval. The process signals an out-of-control condition when C_t^+ or C_t^- exceeds H.

A practical illustration of this integration is in monitoring pH levels in hydroponic farming. Over six weeks, daily pH measurements are recorded $(x_{t,j})$ where t=1,2,…,6 represents weeks and j=1,2,….., n_t represents daily readings. Each week's pH readings are ordered, and the weekly mean $\bar{X}$ is calculated. This Ordering helps identify trends within weekly data, ensuring that the calculated mean reflects the process's true central tendency. The overall mean μ_0 is derived from the six weekly means representing the stable baseline for pH levels in the system. Using μ_0 as the baseline, the CUSUM chart then tracks deviations in daily pH levels from this target, signalling potential issues when the cumulative sums exceed the decision interval H and also ensures optimal nutrient levels, maintaining stability and consistency in plant growth. The chart also supports flexibility and customization, allowing parameters such as the reference value and decision interval to be designed to fit specific processes. This adaptability ensures that it can be applied effectively across broad sectors, from manufacturing to agriculture. In hydroponics, the capability to detect slight pH fluctuations ensures that nutrient availability is maintained at optimal levels for plant growth, directly improving yield quality and consistency. By maintaining key parameters within optimal ranges, the system ensures that plants experience minimal stress and grow under ideal conditions. This is particularly important in commercial hydroponic operations, where uniformity in size, weight, and quality of produce is critical for marketability. The continuous monitoring enabled by the CUSUM chart helps identify and rectify issues that might compromise yield quality, ensuring that each plant achieves its growth potential. Its focus on early detection and targeted intervention makes it a valuable tool for optimizing performance, preserving resources, and ensuring consistent outcomes in any system where precision and control are essential.

Modern hydroponic systems equipped with sensors can continuously feed data into centralized monitoring units, where algorithms based on order statistics and CUSUM methodologies process the information. This systematization reduces the need for manual intervention, enhances precision, and ensures that potential issues are detected and resolved quickly. Additionally, the system-generated alerts and recommendations enable growers to make quick, informed decisions, minimizing downtime and maximizing productivity. This integration not only enhances the system's productivity but also aligns with the global push for sustainable agricultural practices by reducing resource consumption and environmental impact.

3. Methods

The study was conducted in hydroponics to test whether the wider range of pH 5.0 to 6.9 can affect the plant height of water spinach. The optimal pH range for water spinach is between 5.5 and 6.5. To check the stability and consistent relationship of plant height is between wider pH range 5.0 to 6.9. The data were analysed by using CUSUM control chart as it is particularly helpful in determining when the assignable cause have occurred and is more effective in detecting small process shifts. A Google database was used to collect data on plant growth at levels of pH ranging from 5.5 to 6.9 during a 6-week period. The monitoring occurred until the end of the growing season, completing 6 weeks of evaluation. Subsequently, the samples were arranged according to the order statistics method. The analysis of the statistical process control was carried out using control charts. The CUSUM control chart model selected for this study generates a control chart for detecting small shifts of variation in the process. (Montgomery 2009) [6].

3.1 Procedure of Tabular CUSUM chart:

Montgomery defines the CUSUM may be constructed both for individual observations and for the averages of rational subgroups.

Step 1

The CUSUM chart,

The General form of CUSUM is given by this formula

$C_t = \sum_{i=1}^{t} (x_i - \mu_0)$

n = sample number

μ_0 = target value

C_t = sum of the deviations from target for all observations upto and including the t^{th} observation.

x_t = the t^{th} observation.

Step: 2

The Tabular CUSUM chart:

The statistics are called one-sided upper and lower cusums.

Upper control limit = $C_t^+ = \max(0, x_t - (\mu_0 + K) + C_{t-1}^+)$

Lower control limit = $C_t^- = \max(0, (\mu_0 - K) - x_t + C_{t-1}^-)$

Where the starting values are $C_0^+ = C_0^- = 0$

Step: 3

K is called the reference or allowable value, $K = \frac{1}{2} \cdot |\mu_1 - \mu_0|$

Step: 4

H is called the reasonable value, H=5σ

Step: 5

If the value of C_t^+ and C_t^- exceeds the decision interval H, the process is said to be out of control. Cumulative sum deviation above the target draws an increasing line exceeding the upper limit which means the process has shifted and may be affected by specific variable. In this situations, an adjustment to some manipulatable variable is required in order to bring the process back to the target value due to out-of control.

Step: 6

The new process mean can be computed by the equation below and from this equation, we would estimate the new process average that stays within the upper and lower limit, follow the equation (2.7).

4. Results and Discussion

In hydroponic systems, pH is constantly varying as the plant grows. Changes in pH of less than 0.1 unit are not significant. Thus pH control is a necessity in hydroponic solutions. The pH range of 5.5 to 6.5 is optimal for the availability of nutrients from most nutrient solutions for most species, but species differ significantly as they can grow well outside of this range, Islam *et al*. (1980)]. The PH requirements for species commonly grown in growth chambers are provided.

Several species can grows well at pH values that exceeds the recommended range of 5.5 to 6.5 (Sardare M.D and Admane S.A (2013)) although for most (conventional) vegetable species plant growth is impaired at pH levels above 7.0 or under 5.0. pH plays a significant role in hydroponic systems as it affects the solubility of nutrients in water. Different plants require different pH ranges to absorb nutrients effectively. For water spinach, a leafy green vegetable that grows well in hydroponics, maintaining the pH within a specific range is essential for optimal nutrient uptake. This study suggests that the optimal pH range for water spinach is between 5.5 and 6.5, but a wider range (5.0 to 6.9) which was used in this experiment to observe the full spectrum of potential plant responses. The CUSUM control chart is a statistical tool designed to detect small shifts in the process mean over time. Unlike other control charts that only detect larger deviations, the CUSUM chart is highly sensitive that accumulates deviations from a target value, making it an ideal tool for monitoring gradual changes in pH levels or plant growth. In this study, two separate CUSUM charts were created: one for pH levels and another for plant growth data. The pH level was monitored to ensure that it remained within the expected range, while the plant growth data was analysed to observe any other shifts in growth patterns over time.

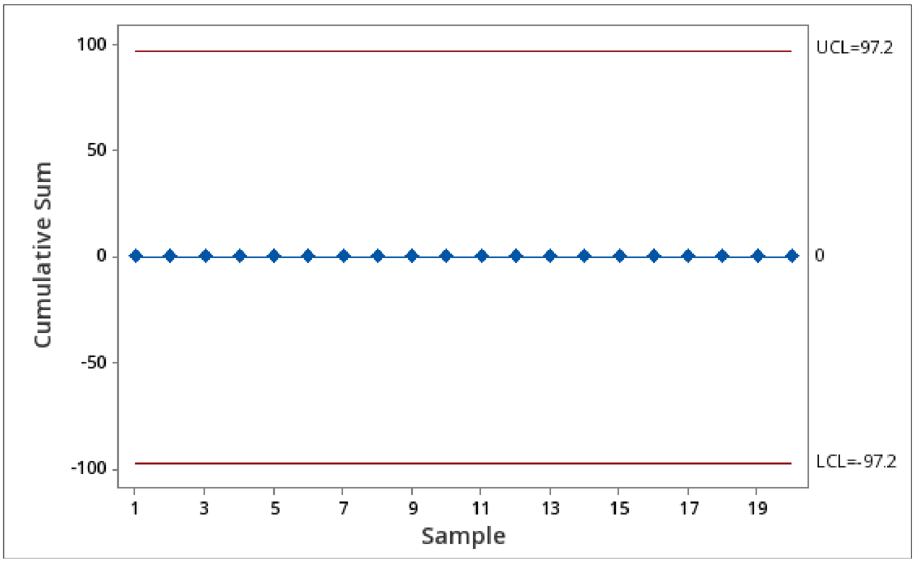

Fig 1: CUSUM Chart for Plant height mean

Figure 1 shows that the results from the CUSUM charts for both pH levels and plant growth of water spinach indicate that it is stable. This is an encouraging result for hydroponic growers, as it implies that maintaining a strict pH range may not be necessary, and slight fluctuations in pH may not negatively affect plant growth.

5. Conclusion

In this paper a new process control mechanism is developed through the order statistics under the CUSUM charts. This is an encouraging result for hydroponic growers, as it implies that by maintaining a strict pH range may not be necessary and there is a slight fluctuation in pH which may not negatively affect plant growth. This study develops a system, in hydroponics the plant's growth is well at an optimal pH level; suppose if there is a high pH level in the nutrient solution which can lead to nutrient deficiencies and poor plant performance. The results have shown that hydroponic growers can maintain a slightly wider pH range without compromising plant health, which may reduce the need for constant pH adjustments and monitoring. The yielding crop has higher the growth rate than the manual method which implies an alternative way to study the hydroponics cultivations under process control will improve the accuracy of the conclusion made through the hydroponics cultivations.

6. Acknowledgements

The authors are happy to acknowledge the comments and helpful suggestions made by an anonymous referee and the editor of the journal and our parent University for providing necessary facilities in the Department.

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