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Fertilizer Application Levels in Potato Crops and the Diagnosis and Recommendation Integrated System (DRIS)

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Abstract: The rates of nitrogen, phosphorus, and potassium fertilizers used in the cultivation of potatoes are often considered excessive, as they can cause imbalance among the essential elements present in the soil. Using leaf nutrient analysis, this study aimed to evaluate the productivity of potato tubers subjected to different rates of nitrogen (N), phosphorus (P), and potassium (K) to establish the diagnosis and recommendation integrated system indices. Three experiments were conducted, one for each nutrient (N, P, and K), with Agata and Atlantic cultivars in Unaí (Minas Gerais state) and the Agata cultivar in Mucugê (Bahia state). The nutrient rates were 0, 30, 70, 120, and 280 kg ha^{-1} of N; 0, 150, 300, 600, and 900 kg ha^{-1} of P_2O_5; and 0, 70, 110, 220, and 450 kg ha^{-1} of K_2O. Agata and Atlantic had adequate nutritional balance under K application. Agata had a more adequate nutritional balance under P application in Mucugê, whereas K fertilization was more decisive for the nutritional balance in Unaí. The differences in the results can be explained by the different soil textures and nutrients in the soil between the regions. The results show the need to consider the soil conditions and the nutrient uptake/translocation capacity of cultivars before establishing rates to increase production revenue and avoid the waste of fertilizers.

Keywords: fertilization; nutritional balance; nitrogen; phosphorus; potassium; *Solanum tuberosum*

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1. Introduction

Potato (*Solanum tuberosum* L.) is the fourth-most consumed food in the world, after rice, wheat, and corn [1]. Potatoes are fast-growing, adaptable, high-yielding, and attractive crop options for developing countries [2]. There is considerable potential to increase potato production by improving water use and optimizing field management [3,4]. Nitrogen (N), phosphorus (P), and potassium (K) fertilizer application increases the tuber size and weight and reduces the number of non-marketable tubers. Therefore, it is relevant for studies to identify the required amount and distribution of nutrients [5].

Nutrient imbalance in the soil reduces the uptake of some nutrients, which affects the health of the plants [6] making them more sensitive to stress conditions. Hemmati and Mansoori [7] remarked on the relevance of nutritional management to prevent and control plant diseases. Appropriate nutritional management contributes to successful cropping, production cost reduction, and more sustainable agriculture.

Among the available mechanisms for optimizing fertilization recommendations, techniques that identify nutrient uptake during the entire plant lifecycle, such as leaf nutrient analysis, are essential. Such analyses provide information on the nutritional state of the plant at a low cost [8], and can be used to compare the results in different cropping areas that provide conditions to improve fertilization management.

The results of the leaf nutrient analysis can be interpreted using several methods that can determine the adequate ranges of nutrients or critical levels in plant tissues for different parts of the plants separately and without the need for calibration tests [9].

The diagnosis and recommendation integrated system (DRIS) is a nutritional diagnosis method commonly used for cereals and oilseed crops, but can also be used for many other crops [10]. The diagnosis calculated by the DRIS, which is considered a reference, is based on the correlation between the nutrients taken up by high-productivity plants. The appropriate correlations are referred to as "standard" and identify those nutrients taken up in low quantity, appropriate levels, or even in excessive amounts [10,11].

The DRIS index values suggest which nutrient is the most limiting, and also can provide the limiting sequence of all the nutrients [12]. Positive and negative indices refer to nutrition excess or deficiency, respectively, and a DRIS index of zero or close to zero indicates nutritional balance [13]. The DRIS method also indicates antagonism between nutrients and allows greater flexibility in sampling [14].

The application of methods such as DRIS enables the establishment of regional nutritional standards, which are substantive once these types of regional patterns are better defined and reliable compared to general values [15]. These regional standards contribute to the rational use of fertilizers for increased production [16], avoid the waste of mineral resources and money, and consequently are more efficient [17]. The advantages of DRIS were reported in studies with bananas [18], pineapples [19], palms [20], and potatoes [21].

The uptake of nutrients and their use are complex processes, in which nutrients interact through chemical reactions during plant lifecycles. The stoichiometry of nutrients has been studied to provide relevant information regarding nutrient uptake and distribution in plants [22]. Therefore, tools such as DRIS can help understand the relationship between nutrients and soil science and must be considered. Scucuglia and Creste [23] stated that DRIS is an efficient and cheap option for establishing nutrient patterns, even for small plantations and properties. For future crops, the provided data will guide better nutritional management and an increase in production [24].

In Brazil, the cultivar Agata stands out due to its high yield and quality of tubers for the fresh market. For processing into potato chips, the most cultivated is Atlantic. The amounts of nutrients taken up for potato cultivars are different and this is reflected in tuber yield [21,25]. To analyze the difference between the main potato cultivars grown in Brazil (Agata and Atlantic), we chose two regions that are highlighted in the cultivation of this culture, located in the states of Bahia and Minas Gerais. Using leaf nutrient analysis, the present study aims to evaluate the productivity of potato tubers subjected to different NPK fertilization rates to establish the DRIS indices.

2. Materials and Methods

2.1. Site, Soil, and Climate

The cultivation of the Agata and Atlantic potato cultivars was undertaken in Unaí, Minas Gerais (MG), at 6°21′27″ S and 46°54′22″ W, 640 m altitude, Awi climate in the Köppen climate classification, and with a clay-textured soil classified as dystrophic red latosol [26], from May to August and June to September 2014, respectively. The maximum and minimum temperatures from May to August varied from 29 to 37 °C and 9 to 14 °C, respectively, and from June to September varied from 29 to 40 °C and 9 to 17 °C, respectively. The relative humidity ranged from 51% to 68% and 52% to 64% from May to August and June to September, respectively. The total rainfall was 50 and 57 mm from May to August and June to September, respectively.

In Mucugê, Bahia (BA)—13°00′19″ S and 41°22′15″ W, 986 m altitude, Cfb climate according to the Köppen classification, and soil with a medium texture classified as red-yellow latosol [26]—an experiment was conducted with the Agata cultivar from September to December 2014. The maximum and minimum temperatures during the study period ranged from 25 to 29 °C and 12 to 16 °C, respectively. The relative humidity ranged from 62% to 80%, and the total rainfall over the study period was 350 mm.

In these experiments, potato plants were grown under center-pivot irrigation, supplied with sufficient water for the full development of the crop (500–550 mm) throughout the cultivation period. Generally, a 6 mm water depth was applied in both areas, every 2 days, from emergence to hilling up; 10 mm during vegetative development; and 12 mm, every 3 days, in the stolonization and tuberization phases. Phytosanitary care was undertaken as required based on the monitoring of pests, diseases, and weeds using products registered for the potato crop and at rates recommended by the manufacturers.

All experiments were conducted in fields used for potato production. Before planting, soil sampling was performed in the 0–20 cm layer, and the samples were chemically analyzed following the method described by [26]. The values are listed in Table 1.

Table 1. Soil chemical characterization before planting and before fertilization (BA: Bahia; MG: Minas Gerais).

Soil Characteristics	Mucugê-BA (Agata)	Unaí-MG (Agata)	Unaí-MG (Atlantic)
Water pH value	5.7	5.2	5.3
P (mg dm^{-3})	11.7	14.5	17.0
K (cmolc dm^{-3})	0.21	0.22	0.23
Ca (cmolc dm^{-3})	1.3	2.9	3.2
Mg (cmolc dm^{-3})	0.4	1.1	0.9
H + Al (cmolc dm^{-3})	1.8	3.5	3.6
Cation exchange capacity (cmolc dm^{-3})	3.7	7.7	7.9
Base saturation (%)	51.9	54.6	54.4

2.2. Crop Management, Treatments, and Measurements

Three experiments were conducted for each cultivar and location to evaluate the effects of different rates of N, P, and K. The design was a randomized block, consisting of five treatments (represented by fertilizer rates) and four repetitions, totaling 20 plots for each experiment.

Each plot was composed of six lines (6 m length), with spacing of 0.8 m between rows and 0.3 m between plants, totaling 28.8 m^2 for each plot. The evaluations were performed using two central lines, totaling 8 m^2.

The applied fertilizer rates were 0, 30, 70, 120, and 280 kg ha^{-1} of N; 0, 150, 300, 600, and 900 kg ha^{-1} of P_2O_5; and 0, 70, 110, 220, and 450 kg ha^{-1} of K_2O.

Based on the Comissão de Fertilidade dos Solos de Minas Gerais [27] recommendations, the rates of 120 kg ha^{-1} of N, 480 kg ha^{-1} of P_2O_5, and 220 kg ha^{-1} of K_2O are standard. The N, P, and K sources used were urea, triple superphosphate, and potassium chloride, respectively. At the time of planting, the corresponding micronutrient rates applied were 0.2% zinc, 2% magnesium, 11% calcium, 12% sulfur, 0.08% boron, 0.08% copper, and 0.2% manganese.

After soil preparation (ploughing, harrowing, and furrow opening) the N, P, and K fertilizers were manually spread on the planting furrows and evenly incorporated into the soil with a hoe. Subsequently, seed potatoes were manually placed on the planting furrows.

For N fertilization, 60% of the total amount was distributed on the furrows at planting and 40% was applied to the upper soil at 27 days after planting (DAP), at the same time that earthing up was performed. When necessary, pest and disease control was undertaken by applying registered agrochemicals for potato crops, according to the manufacturer's recommendations.

In all three experiments, at 35 DAP, 20 leaves (leaflets plus petiole) of the third fully formed trefoil were collected. The samples were correctly packaged in Kraft paper bags and subjected to leaf nutrient content analysis.

The samples were cleaned in accordance with Bataglia's [28] methodology and kiln-dried (65 ± 5 °C); then the macronutrient (N, P, K, Ca, Mg, and S) and micronutrient (B, Cu, Fe, Mn, and Zn) levels were determined [26].

At the end of the experiments (112 DAP for Agata and 115 DAP for Atlantic in Unaí-MG, and 106 DAP for Agata in Mucugê-BA), the tubers were manually harvested (discarding 0.5 m on the extremes), classified, and weighed using an electronic balance. Productivity was calculated for each plot, and the values were converted to kg ha^{-1}.

2.3. Calculated Parameters

From the leaf nutrient content and productivity values, the DRIS indices were calculated. The productivity of each plot for each treatment was treated as a different population result. The groups of populations were evaluated and divided into two general groups: low and high productivity. Production of approximately 44.35 and 53.0 t ha^{-1} were considered as standard levels for Agata/Unaí-MG and Atlantic/Unaí-MG, and Agata/Mucugê-BA, respectively. The populations were separated based on these standard measures.

Productivity, DRIS indices, and nutritional balance (IBN) values were calculated using Excel software (Microsoft) and the Beaufils method [12,29] (Equations (1)–(4)):

$$if : \frac{Y}{X_a} < \frac{Y}{X_n} then : \int\left(\frac{X}{Y_a}\right) = \left[1 - \left(\frac{Y}{X_n} / \frac{Y}{X_a}\right)\right] \times \left(100 \times \frac{k}{CV}\right) \quad (1)$$

$$if : \frac{Y}{X_a} = \frac{Y}{X_n} then : \int\left(\frac{X}{Y}\right) = 0\ (zero) \quad (2)$$

$$if : \frac{Y}{X_a} \geq \frac{Y}{X_n} then : \int\left(\frac{X}{Y}\right) = \left[\left(\frac{Y}{X_a} / \frac{Y}{X_n}\right) -\right] \times \left(100 \times \frac{k}{CV}\right) \quad (3)$$

where $\int (Y/X)$ = calculated function for nutrient relations Y and X; Y/X_a = nutrient relation of the sample; Y/X_n = nutrient relation of the standard pattern; s = pattern deviation of Y/X_n; CV = coefficient variation (%) of Y/X_n; and k = sensitivity constant.

$$I_y = \frac{\sum_{i=1}^{m} f(Y/X_i) - \sum_{j=1}^{m} f(X_i/Y)}{m+n} \quad (4)$$

where I_y = DRIS index for Y nutrient; Y = nutrient value; X = another nutrient value; m = number of functions when Y nutrient is on the function denominator; and n = the number of functions when the Y nutrient is on the function numerator.

DRIS calculations allowed the calculation of negative, zero, and positive indices, which correspond to nutrient deficiency, nutritional balance, or extra consumption, respectively [12]. The IBN value was the sum of the DRIS index modulus. The higher the IBN value, the better the nutritional balance.

3. Results

3.1. Agata Cultivated in Unaí-MG

High productivity populations were obtained when nutrient rates applied on furrow planting were 0, 30, 70, 120, and 280 kg ha^{-1} of N; 600 and 900 kg ha^{-1} of P_2O_5; and 0, 70, 110, 220, and 450 kg ha^{-1} of K_2O (Table 1).

For the high productivity group, the most limiting nutrient was B under the higher rate of N application (kg ha^{-1}). For all N and zero application rates, B limitation was verified, and the higher the N rate, the higher the B-limiting effect. However, B had a higher overload uptake in this group under the K zero application rates (kg ha^{-1}).

The 120 kg ha^{-1} N application rate showed the best results among those tested (Table 2). Increasing the K fertilization rates reduced K and P deficiency in plants. A synergetic interaction between K and N was observed, indicating that N fertilization required an extra supply of K. A similar interaction occurred between P and K.

Table 2. Diagnosis and recommendation integrated system (DRIS) indices for macronutrients and micronutrients in high (>44 t ha^{-1}) and low (<44 t ha^{-1}) productivity potato crops, for the Agata cultivar in Unaí-MG (IBN: nutritional balance).

Nutrient (kg ha^{-1})	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn	IBN
DRIS Indices of High Productivity Groups												
N120	−1.26	2.73	−2.85	−0.05	−5.97	−2.36	−9.81	4.35	13.47	3.90	−2.15	48.87
K110	2.32	−7.67	−0.28	−4.57	1.86	−2.77	9.39	6.64	−12.30	8.79	−1.42	58.03
K220	2.54	2.55	−1.12	−12.94	2.58	3.94	9.18	−0.82	−1.76	−0.99	−3.15	41.56
K70	1.66	−8.28	−1.63	5.22	15.51	−2.86	6.57	−12.07	−8.20	3.23	0.86	66.08
N30	−7.07	1.14	0.63	12.48	−6.18	−3.48	−1.20	14.79	8.80	−13.65	−6.25	75.67
N70	−4.27	8.22	1.20	7.35	−3.39	6.18	−6.07	6.35	2.49	−1.65	−16.42	63.57
K450	3.56	7.22	3.04	−6.34	−1.38	−0.92	−6.85	9.21	−1.08	−4.33	−2.13	46.06
K0	0.27	−12.70	−12.66	6.40	15.90	−1.96	16.17	−16.04	−1.78	−1.83	8.23	93.94
N280	−5.02	−4.54	−1.89	0.17	−5.65	3.28	−19.81	4.77	14.33	15.15	−0.79	75.40
P600	5.02	8.37	4.26	−5.16	−7.75	2.19	−5.19	−8.87	−9.02	2.73	13.42	71.98
N0	−8.89	1.80	3.18	6.95	−5.58	0.00	−1.49	13.97	7.34	−11.30	−5.97	66.48
P900	7.54	7.43	4.31	−5.18	−0.61	−7.25	8.46	−11.93	−7.02	−6.57	10.81	77.11
												65.40
DRIS Indices of Low Productivity Groups												
P0	9.96	−25.79	15.52	−15.94	−6.29	12.22	−3.70	−16.10	−0.94	22.93	8.12	137.50
P150	10.96	−36.69	16.35	−14.62	−3.11	33.91	−4.47	−6.20	−7.20	4.76	6.33	144.59
P300	9.87	−34.79	19.53	−15.17	−1.04	10.66	−8.68	−8.11	0.35	9.84	17.55	135.59
												139.23

High P application rates did not cause limitations of N, P, K, and Zn. For the N rates tested, no restriction of Cu and Fe were observed (Table 2). Fe restriction was not observed because of its high pre-existing levels in the soil. For all K rates, N limitation was not observed owing to their synergetic interaction; however, higher fertilization required an additional supply of K fertilizer.

In the high productivity group, among the macronutrients, Ca was the most limiting, reaching a higher index under the 220 kg ha^{-1} K_2O application in furrow planting, followed by P and K in the K zero application rate. Therefore, K fertilization most affected the high productivity group for the evaluated rates (Table 2).

For the micronutrients in the low productivity group, high limitation indices for B, Zn, and Cu were observed when submitted to 280 kg ha^{-1} of N, 70 kg ha^{-1} of N, and K zero application rate, respectively (Table 2).

In the high productivity group, the population with a better IBN index was found in the 220 kg ha^{-1} K_2O application rate. For this population, although a limiting effect was observed for Ca, the nutritional balance between the other nutrients was satisfactory and did not cause a production decrease, which reinforces the need to consider and understand the system as a whole. The zero and maximum rates of P_2O_5 applied to furrow planting prejudiced the nutritional balance (high IBN indices); however, it did not affect production (Table 2).

In the low productivity group, N, K, S, Mn, and Zn did not show limiting indices for productivity. P and Ca were the most limiting nutrients when the populations were subjected to 150 and 300 kg ha^{-1} P_2O_5 fertilization, respectively.

Comparing the two groups, a higher nutritional imbalance was observed for the low productivity populations; therefore, the nutrient correlation influenced uptake, effects on plants, and productivity (Table 2). Thus, a proper balance between the taken-up nutrients is as relevant as the amount of uptake.

3.2. *Atlantic Cultivated in Unaí-MG*

High productivity was obtained when the nutrient rates applied to the furrow plantings were 70, 120, and 280 kg ha^{-1} of N; 300, 600, and 900 kg ha^{-1} of P_2O_5; and 0, 70, 110, and 220 kg ha^{-1} of K_2O (Table 3).

Table 3. DRIS indices for macronutrients and micronutrients in high (>35 t ha^{-1}) and low (<35 t ha^{-1}) productivity potato crops, for the Atlantic cultivar in Unaí-MG.

Nutrient (kg ha^{-1})	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn	IBN
DRIS Indices of High Productivity Groups												
N120	7.52	1.04	8.89	−0.61	−14.25	3.41	−3.11	−4.44	−6.25	8.04	−0.25	57.83
P600	−8.02	−2.64	3.29	2.08	6.04	−5.03	5.46	−1.77	12.67	−12.13	0.05	59.18
K110	10.28	−7.08	−10.00	−1.09	1.50	−2.02	−3.75	12.33	−5.40	2.84	2.40	58.68
P300	−13.90	−4.36	1.35	2.28	8.72	−3.25	8.91	0.18	4.92	−3.95	−0.92	52.73
N280	15.74	12.60	10.43	−10.41	−11.19	−2.65	0.80	−2379	−4.40	22.14	−9.27	123.41
N70	−4.53	2.99	6.83	−2.03	−12.63	−4.11	−5.59	−0.95	9.86	8.53	1.63	59.68
P900	−3.92	16.38	4.28	14.90	9.85	−13.75	−1.05	−5.07	−6.40	−15.00	−0.21	90.80
K220	0.13	1.62	−10.03	−4.87	−2.73	4.39	−20.33	9.99	8.36	5.53	7.93	75.90
K0	1.37	−7.14	−10.51	2.13	8.91	10.26	9.44	1.91	−13.47	−2.89	−0.02	68.04
K70	3.18	−3.03	−7.51	−4.47	6.55	11.21	4.87	1.46	−7.94	−2.09	−2.23	54.53
												70.08
DRIS Indices of Low Productivity Groups												
N30	12.78	−46.28	3.09	−3.70	−16.56	11.56	8.83	15.36	16.34	−5.38	3.94	143.84
P150	−11.54	−2.45	4.81	9.54	10.48	−12.68	3.67	0.72	4.48	−4.34	−2.71	67.42
N0	11.06	−47.97	10.08	1.41	−19.05	24.35	21.92	14.19	7.00	−23.03	0.04	180.10
P0	−11.83	−2.72	6.34	14.28	14.28	0.47	13.25	−14.42	−9.67	−9.77	−0.22	97.25
K450	1.51	−10.58	2.67	−6.54	−14.59	−10.00	−20.06	19.02	11.94	18.42	8.19	123.51
												122.42

For both high and low productivity groups, the higher levels of nutritional imbalance were related to N fertilization. High N application rates caused a negative effect in the high productivity groups, and the zero application rates caused even poorer results. The negative effect of the high N application rates could be minimized by increasing the K fertilization rates.

The 120 kg ha^{-1} N application rate resulted in higher productivity for both the Agata and Atlantic cultivars in Unaí-MG. The use of 110 kg ha^{-1} of K_2O showed one of the best productions for the two cultivars (Table 3). However, it cannot be affirmed that the combination of the two rates would show the same result because it also depends on the correlation between the other nutrients.

Atlantic had a better response to P fertilization than Agata in Unaí-MG. In addition, the Atlantic cultivar was more affected when subjected to P and K zero application rates than was Agata; it showed low productivity and was eventually classified into the low productivity group (Table 3).

For P fertilization, the increase in rates reduced the limitation of N and P; however, it restricted S, B, Cu, and Mn uptake. K, Ca, and Mg limitation for all P application rates tested was observed (Table 3).

K fertilization stimulated the uptake of Fe, Mn, and Zn, and did not show a limiting effect on N and Cu uptake (Table 3). Fe and Mn are more soluble under acidic pH conditions [30], which might have facilitated the uptake of these nutrients during the experiment.

A higher limitation of macronutrients was observed in the following situations: limitation of Mg in the 120 kg ha^{-1} N application, limitation of N in the 300 kg ha^{-1} P_2O_5 application, and limitation of S in the 900 kg ha^{-1} P_2O_5 application (Table 3). Thus, an increase in P fertilization caused better uptake of N and restriction of the S supply. All these chemicals were taken up in the ionic state; therefore, there was a clear interaction between all nutrients that affected the uptake.

In the low productivity group, when under P zero fertilization rate the most limiting nutrient was P, and there was overload uptake of S. However, K limitation was not observed (Table 3). Low rates of N promoted P and Mg limitation, and high rates of K caused B and Mg limitation and overload uptake of Cu and Mn.

In the low productivity group, Mn limitation was observed for all tested rates except for the 450 kg ha^{-1} of K fertilization. In addition, under the same application, the only nutrient that had its uptake changed was B (Table 3).

3.3. *Agata Cultivated in Mucugê-BA*

High productivity was obtained when the nutrient rates applied to the furrow plantings were 70, 120, and 280 kg ha^{-1} of N; 150, 300, 600, and 900 kg ha^{-1} of P_2O_5; and 110 and 220 kg ha^{-1} of K_2O (Table 4).

Table 4. DRIS indices for macronutrients and micronutrients in high (>53 t ha^{-1}) and low (<53 t ha^{-1}) productivity potato crops, for the Agata cultivar in Mucugê-BA.

DRIS Indices of High Productivity Groups												
Nutrient (kg ha^{-1})	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**B**	**Cu**	**Fe**	**Mn**	**Zn**	**IBN**
P600	−1.34	−4.57	3.79	4.91	9.91	1.44	5.31	−10.67	3.28	−7.15	−4.90	57.26
P300	1.22	0.81	−2.48	4.76	8.52	9.10	−0.88	−5.32	−9.33	−4.47	−1.93	48.82
K110	−9.04	−6.11	−0.34	4.31	5.09	1.13	−12.76	1.68	14.94	−6.97	8.08	70.45
N280	17.75	8.47	−1.28	−12.01	−15.76	−11.88	7.08	1.02	−1.74	4.77	3.58	85.34
N120	9.72	11.54	2.20	−13.00	−16.13	−12.35	9.64	11.59	−1.57	−0.72	−0.93	89.39
N70	−7.56	4.19	2.30	−11.46	−20.97	−1.98	15.68	13.06	4.60	12.49	−10.35	104.65
K220	−6.74	1.14	−0.86	9.02	9.11	−4.67	−17.01	3.89	1.57	−0.55	5.08	59.65
P900	1.61	−2.90	7.50	5.75	2.12	4.51	−3.42	−8.60	2.41	−1.56	−7.44	47.82
P150	1.99	−5.09	−5.27	1.76	10.55	7.00	−5.74	−1.27	−9.59	2.98	2.67	53.91
												68.59
DRIS Indices of Low Productivity Groups												
P0	1.59	−11.82	−11.30	2.42	12.30	3.41	−18.82	9.87	−15.38	8.45	19.28	114.63
K0	−7.38	−9.02	−5.17	9.52	5.09	5.26	0.28	−9.47	13.76	−10.19	7.32	82.46
K70	−7.75	−15.20	−5,50	10.23	8.32	6.81	2.28	−18.50	23.60	−9.67	5.39	113.26
N30	−12.64	−6.28	533	−6.88	−18.57	−1.36	20.61	8.69	−12.00	17.20	5.90	115.45
K450	−0.49	−6.29	3.08	−4.64	−2.16	3.15	−15.89	5.02	9.83	−1.25	9.63	61.44
N0	−9.47	0.66	−3.44	−9.17	−20.53	−1.69	14.79	0.93	−5.17	17.64	15.44	98.94
												97.70

In the high productivity group, N fertilization caused Mg limitation, and the 280 kg ha^{-1} N application rate resulted in the overload uptake of N (Table 4). For the 120 and 280 kg ha^{-1} N application rates, an excess of N was observed in the plants and there was Ca and Mg limitation (Table 4).

For P fertilization, except when applying the 300 kg ha^{-1} rate, all tested rates resulted in P limitation (Table 4). The use of higher levels of P fertilizer gradually increased K and Ca availability, reduced Mg availability, and caused higher Zn limitation. However, the increase in K fertilization decreased N, P, and Mn limitation, and caused higher K and B limitation.

In the present study, we did not verify the direct interaction between higher IBN values and ideal productivities as we did in the Atlantic experiment in Unaí-MG; yet, there was a difference from what happened to the Agata cultivar in Unaí.

For micronutrients, the most limiting nutrient was B in the 220 and 110 kg ha^{-1} of K_2O applications in the high and low productivity groups, respectively, and under the zero application rate of K_2O. In the low productivity group, no Zn limitation was observed (Table 4).

The Agata and Atlantic cultivars showed different nutrient demands and photosynthetic conversion behaviors. In addition, planting time, soil characteristics, and macro and microclimate conditions influenced plant metabolism. All these factors interact and result in different plant responses, which are expressed as different productivity.

Considering the standard productivities of 35 t ha^{-1} for Atlantic in Unaí-MG, 44 t ha^{-1} for Agata in Unaí-MG, and 53 t ha^{-1} for Agata in Mucugê-BA, an increase of 17% in Agata in Mucugê-BA compared to Unaí-MG, and an increase of 20.5% for Agata compared to Atlantic (both in Unaí-MG) was observed.

The order of deficient nutrients in the high and low productivity areas, respectively, as shown in Table 5, was: Agata in Unaí-MG: Cu > P > B > Ca > Fe > Mn > N > Zn > Mg > K > S and P > Ca > Cu > B > Fe > Mg > N = K = S = Mn = Zn; Atlantic in Unaí-MG: Mg > K > N > Fe > Cu > B > S > P > Mn > Ca > Zn and P > B > Mg > Cu > N > S > Mn > Fe > Ca > Zn > K; and Agata in Mucugê-BA: Mg > Ca > B > S > Cu > N > Fe > Zn > P > Mn > K e B > Cu > Mg > Fe > P > N > Mn > Ca > K > S > Zn.

Table 5. Nutrient deficiency index for macronutrients and micronutrients in high and low productivity areas for cultivars Agata, Unaí-MG; Atlantic, Unaí-MG; and Agata, Mucugê-BA.

Agata, Unaí-MG				Atlantic, Unaí-MG				Agata, Mucugê-BA			
High Productivity		Low Productivity		High Productivity		Low Productivity		High Productivity		Low Productivity	
Cu	−9.95	P	−32.42	Mg	−10.20	P	−22.00	Mg	−17.62	B	−17.35
P	−8.30	Ca	−15.24	K	−9.51	B	−20.06	Ca	−12.15	Cu	−13.99
B	−7.20	Cu	−10.14	N	−7.59	Mg	−16.73	B	−7.96	Mg	−13.75
Ca	−6.84	B	−5.62	Fe	−7.31	Cu	−14.42	S	−7.72	Fe	−10.85
Fe	−5.88	Fe	−4.07	Cu	−7.20	N	−11.68	Cu	−6.46	P	−9.72
Mn	−5.76	Mg	−3.48	B	−6.77	S	−11.34	N	−6.17	N	−7.55
N	−5.30	N	0.00	S	−5.13	Mn	−10.63	Fe	−5.56	Mn	−7.04
Zn	−4.78	K	0.00	P	−4.85	Fe	−9.67	Zn	−5.11	Ca	−6.90
Mg	−4.56	S	0.00	Mn	−4.67	Ca	−5.12	P	−4.67	K	−6.35
K	−3.40	Mn	0.00	Ca	−3.91	Zn	−1.46	Mn	−3.57	S	−1.52
S	−3.09	Zn	0.00	Zn	−2.57	K	000	K	−2.05	Zn	0.00

4. Discussion

We found many interactions between the rates of the principle nutrients applied in the soil and the nutrients' foliar concentration. Each cultivar revealed differences according to changes in metabolism between Agata and Atlantic. On the other hand, the location expresses the dynamic based on the type of soil. The leaf analysis can be seen as an easy and inexpensive way to improve the efficiency of fertilization, as there is a complementarity between soil and leaf analysis as already reported by Srivastava [31].

In general, the main interesting fact we observed was the complex relationship between the nutrient rate and the location where the potato plant was growing, according to IBN. The nutrients when applied excessively or not applied generated an unbalanced variable according to which nutrient was applied (N, P, or K) and this reflects on productivity (that is, according to the nutrient and its function); even if the rate is excessive, the potato plant could manage to overcome the disproportion between the nutrients and generate high productivity, but the opposite can also happen (excessive rates do not generate a large imbalance but do generate a pronounced drop in productivity).

Analyzing Tables 1–3, we observed that extreme rates generated large imbalances between the nutrients in the plants. However, it does not always happen; we observed that in low rate of P (150) in Atlantic and high rate of K (450) in Agata (Mucugê-BA), there was low IBN but low productivity. We can see the opposite in K (450) in Agata (Unaí-MG), which presented low IBN but high productivity.

The use of high nutrient application rates might cause unnecessary uptake by the plants and not increase production [25,32]. Queiroz et al. [21] reported that low IBN indices indicated plants with good nutritional balance and high production. In contrast, among the high productivity group in the present study, the lowest productivity was obtained by the population with the second-best IBN index. Therefore, it is vital to consider other interactions and conditions, not just nutritional factors [33]. DRIS is a useful tool to help in decision-making because it indicates a path to follow. Further studies are required to fully comprehend the nutritional system.

The performance of Agata and Atlantic in Unaí-MG is related to adequate nutritional balance under K application while Agata in Mucugê-BA had a more adequate nutritional balance under P application. The soil with higher sand content reflects less retention of nutrients, so the extreme rates (zero and high rates) were more harmful to potato production in Mucugê-BA. The limitations and excesses of nutrients in the leaves of potatoes are related to the dynamic between the soil contents and the amount of nutrients applied. In Agata (Unaí-MG) the B-limiting effect (for N zero application rate) and its overload uptake (for K zero application rate) showed that a higher limiting effect under increased N and K rates can be explained by plant growth. Higher fertilizer rates, especially for N, promoted further development and growth, which caused a higher dilution of B in plant tissues. Higher N and K fertilization also provided an extra supply of B (Table 2). Freiberger et al. [34] observed a B-limiting effect when high rates of N were applied during a cedar tree experiment.

B is a structural component of the cell wall. The low availability of B causes structural damage in xylem vessels prejudicing water transportation, which can negatively affect photosynthesis. Foliar fertilization to supply extra B must be performed properly, as alterations in leaf surface properties can reduce nutrient uptake by foliar fertilization [35].

According to Gupta and Solanki [36], a regular supply of B is required for plant growth. However, micronutrients such as B display a narrow margin between deficiency and toxicity, and technical monitoring is required to prevent a decrease in production.

The three experiments show high yields as rates of N increase. In the same growing location, Atlantic is more demanding in N and less demanding in P than Agata.

N levels determine the number of enzymes present in the plant, which lead to structural modifications. Upper N rates reduce the biosynthesis of lignin, and the plant consequently becomes less resistant to pathogens [37]. Plants that are more susceptible to pathogens show a decrease in production [38]. The 120 and 280 kg ha^{-1} N rates resulted in high productivity, and the 120 kg ha^{-1} N rate also showed good nutritional balance.

Atlantic (Unaí-MG) and Agata (Mucugê-BA) did not respond to the high rate of K (450). This rate may have generated an excessive concentration for the cultivar (Atlantic) and in the soil solution in Mucugê-BA. Although K is a monovalent cation (i.e., it has a lower attraction to soil colloidal structures), its force of attraction can be enhanced by increasing its concentration in the soil and dislocating cations with larger ionic radii [39]. Thus, it is important to prevent excess K because it could reduce the distribution and uptake of $NH_4{}^+$, Ca^{2+}, and Mg^{2+} and prejudice the nutritional balance between the other nutrients [40,41]. Proper attention must be given to the balance between cations and cationic exchange capacity (CEC) (Ca/T, Mg/T, and K/T), aimed at reaching and maintaining the proportion of 45:15:5.

Job et al. [42] noted reductions in Ca and Mg concentrations in potato leaves with increasing K fertilization. Based on the dynamics of excess K, Anjos et al. [43] reported that high K levels promote the percolation of Ca and Mg to the lower soil layers, limiting the availability of Ca and Mg to the plants. In addition, N fertilization changed the cation exchange capacity; however, in this situation, it would enhance the ion exchange between nitrate and $Ca^{2+}/Mg^{2+}/K^+/Al^{3+}$, which means better uptake of these nutrients by the plant [44].

When high K levels were applied, Gott et al. [8] and Koch et al. [45] observed a negative effect on Mg uptake due to their antagonistic interaction. Ca and Mg restrictions, due to high K concentrations, can increase the likelihood of bacterial diseases [41,46,47], reinforcing the necessity to seek a nutritional balance.

Potato yields show high fluctuations between countries, within regions and growing seasons, and are highly sensitive to abiotic and biotic stresses [48–50]. The high productivity in the present study, even though some nutrient limitation was verified, can be explained by the high technological level in the experiments, applying disease and pest control when necessary to maintain plant health and not cause damage. Several complex interactions that do not directly affect productivity are common; however, high limiting levels are more prone to decreasing production, especially when the crop is attacked by pests and pathogens, or affected by unfavorable abiotic conditions.

Despite some limiting effects caused by K fertilization, its application promoted high tuber production and low nutritional balance indices correlated with higher productivity (Table 2).

The action of K in stress resistance is dose-dependent [51,52]. Grzebisz et al. [53] reported that the highest rate of K combined with an increasing rate of N coped with mild water stress. K is the second most abundant nutrient in photosynthetic tissues [54]. K is photosynthetic, acting on RuBisCO activity, CO_2 fixation, and transportation of ions across thylakoid stroma membranes [55,56].

N and K were confirmed and classified as Liebig-synergism [57]. The K nutrient is connected to N uptake and translocation; thus, N and K must be available for the plants in a specific proportion to achieve a satisfactory level of protein synthesis [58]. K can also enhance the activity of microorganisms involved in N transformation via its effects on K channel proteins and osmotic pressure [47]. The higher the amount of N applied to the soil, the higher the requirement for K [59]. However, at an optimum K application level, Grzebisz et al. [53] suggested that N rates could be significantly reduced.

In contrast, Carneval et al. [44] observed that higher levels of N and P promoted greater efficiency of K fertilization. N and P are connected to the inherent properties of plants, as climatic factors and soil conditions. The relationship between N and P should be in harmony with these conditioning factors to achieve high production [60].

N availability in the soil and the proper uptake by plants is related to high productivity, especially during critical periods of crop growth. An extra supply of N in conjunction with Mg can increase production because Mg enhances N uptake [61].

Cu was the most limiting nutrient in the high productivity group in the 280 kg ha^{-1} N application, and the higher overload index was for Mn (under the same N fertilization rate). For all N application rates evaluated, P and K were not limiting; however, the increase of N rates caused Zn restriction (Table 3).

Cu is commonly supplied via agrochemical application. This nutrient is attracted to organic substances and oxides in the soil, and its liberation to plants is favored in acidic soil conditions [62]. This can justify the application of Cu foliar fertilization in the present study, considering that the nutrient could be held in the soil particles and, consequently, was not available to the plants.

Comparing IBN values with limiting and excess indices in the populations subjected to 600 kg ha^{-1} of P_2O_5 (best productivity and medium IBN) and 900 kg ha^{-1} of P_2O_5 (high IBN and medium productivity), the differences between these were higher levels of Mg and B for the 600 ha^{-1} rate, even though there was a small N limitation.

This is a possible interpretation for the interaction between limitation and exceedance, which occurred between the two populations cultivated at the same location and under the same conditions. Even though this could not be the determining factor for the IBN/productivity result, the evaluations allowed us to hypothesize about nutrient relationships and indicate nutritional management adjustments, enabling better decision-making and comprehension of nutrient–soil–plant interactions.

In the low productivity group, Mg was the nutrient with the most limitation, under the zero and 30 kg ha^{-1} N application rates (Table 4). N fertilization promoted better uptake of Mg, indicating that N and Mg had a synergetic interaction. P and Mg also showed a positive correlation. These nutrients are related to energy and chlorophyll molecule production [63], which is beneficial for the photosynthesis process. Frąckowiak et al. [50] using DRIS in potatoes found that a slight imbalance of N and Mg did not disturb tuber yield, provided the balance of K was maintained.

Mg is an important nutrient for plant health as it is related to defense mechanisms against diseases, especially bacterial diseases. A nutritional management system that embraces a proper balance between Mg and other nutrients is an important tool for disease prevention and control [64]. Grzebisz and Potarzycki [59] showed that N and Mg had the most stable trends during tuber yield development.

Despite the results shown here, there are still many details to comprehend for fully understanding the nutrient dynamics. This information allows for a more efficient fertilization method and increase in productivity, based on specific conditions.

5. Conclusions

Agata and Atlantic had adequate nutritional balance under K application.

Agata had a more adequate nutritional balance under P application in Mucugê, whereas K fertilization was more decisive for the nutritional balance in Unaí.

These differences can be explained by the different soil textures and nutrients in the soil stock of the two regions, each of which has particular characteristics and nutrient dynamics.

The results showed the need to consider the soil conditions, nutrient uptake, and translocation capacity of cultivars before establishing fertilizer rates to increase the production revenue and avoid wasting fertilizers.

DRIS is an interesting tool for decision-making and, for producers to be able to use it, it is necessary to gather a sampling of leaves from different crops. Based on leaf (macro and micronutrients) results and productivity, and applying the calculations, the producers can raise the nutritional makeup of the region's soils and better target the application of fertilizers to their crops.

Author Contributions: R.C.O., J.M.Q.L. and R.M.Q.L. conceived the idea of the study. R.C.O., J.M.Q.L. and J.R.R.d.S. conducted the field work. R.C.O., J.M.Q.L., and R.M.Q.L. processed the data and analyzed the results. R.C.O., J.M.Q.L., R.M.Q.L., R.C., A.I.d.A.P. and R.d.C. contributed to the writing original draft. R.C.O., J.M.Q.L., J.R.R.d.S., R.M.Q.L., A.I.d.A.P., R.C. and R.d.C. contributed to revision and edition of the manuscript. J.M.Q.L. coordinated the project. All authors have read and agreed to the published version of the manuscript.

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