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Impact of Gibberellic Acid on Water Status, Growth, and Development of Cape Gooseberry in Newly Reclaimed Sandy Lands within Arid Regions

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Abstract: In newly reclaimed sandy lands, plants face substantial environmental challenges, affecting their productivity, yield, and quality. Gibberellic acid (GA3) is a plant growth regulator physiologically involved in plant responses to abiotic stresses. As agricultural activities expand in desert regions, applications of GA3 could help address adverse plant growth and developmental effects. Here, we investigated the impact of exogenously applied GA3 on the growth of Cape gooseberry (*Physalis peruviana* L.) in newly reclaimed sandy lands in the arid Nubaria region of the West Delta of Nile, Egypt. Different GA3 concentrations of 100, 150, 200, and 250 ppm were foliar-applied to the plants. The application of GA3 in our study significantly improved the vegetative growth, plant height, leaf and branch count, and the fresh weight and yield of Cape gooseberry plants. Fruit weight, quality soluble solids, and leaf chlorophyll content were also improved. The most pronounced effects were achieved with concentrations of GA3 at 200 and 250 ppm, with the 200-ppm concentration displaying superiority in most parameters. Notably, GA3 treatments enhanced relative water content (RWC), an indicator of water status in arid conditions. Maintaining optimal RWC is crucial for essential processes like photosynthesis, promoting growth, and productivity. This research underscores GA3's potential in enhancing Cape gooseberry growth, yield, and quality, providing a practical strategy for mitigating environmental challenges in arid regions, a concern exacerbated by climate change.

Keywords: *Physalis peruviana*; GA3; plant growth; plant growth regulators; fruit weight and characteristics; West Delta of Nile

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1. Introduction

In the intricate realm of agricultural cultivation, the convergence of plant physiology, environmental conditions, and innovative technological solutions plays a critical role in ensuring robust yields.

Cape gooseberry (*Physalis peruviana* L.) belongs to the family *Solanaceae*. The plant can be grown well under temperate, tropical, and sub-tropical climatic conditions [1]. Additionally, the fruit of this plant has many nutritious benefits. Singh et al. [2] indicated that it is a good source of vitamin A, pectin, minerals such as calcium and phosphorus, fibre, and several bioactive compounds. The fruits can be eaten raw in salads and desserts, as a flavouring, and in jams and jellies [3]. The crop's natural flavour suits the fruit processing industry [4].

Plant growth regulators (PGRs) encompass naturally occurring or synthetic compounds that affect developmental and metabolic processes in higher plants, typically at low concentrations. These compounds lack nutritional value and generally do not exhibit phytotoxic properties. PGRs find extensive use in contemporary agriculture, horticulture, and viticulture [5]. Generally, applying PGRs could be a valuable solution to increase crop production [6]. They enable active control over numerous plant developmental and physiological processes, such as hastening or delaying seed germination, breaking dormancy in woody perennials, enhancing or suppressing shoot elongation, prompting flowering and fruiting, regulating fruit set quantity, and influencing senescence-related events like fruit ripening and defoliation [7].

The principal classes of traditional PGRs include auxins, gibberellins, cytokinins, abscisic acid, and ethylene [6]. Among PGRs, gibberellic acid (GA3), an endogenous tetracyclic diterpenoid plant hormone, regulates growth and developmental aspects of crop plants. GA3 is pivotal in mitigating abiotic stress-induced perturbations in plants by modulating various physio-biochemical and molecular processes [8]. Almost 140 different GAs can be found in higher plants and gibberellin-producing fungi. However, most of them serve as precursors or catabolites, with only a few having independent biological activity [6]. According to Singh and Lal [9], applying exogenous GA3 accelerates cell division and elongation at the sub-apical meristem, enhancing tomato plant growth and fruit quality. One of the effects of GA3 is the promotion of fruit setting, development, and quality. For instance, increasing the concentration of gibberellic acid increases the fruit size, fruit weight, total soluble solids, and ascorbic acid level of Cape gooseberry plants [10]. Treatments with GA3 are further known to enhance the quality of spinach plants [11]. Previous studies have shown that the application of GA3 significantly improves the growth and yield of Cape gooseberry plants [4,7,12].

The inclusion of newly reclaimed desert lands in Nubaria, west of the Nile Delta, aligns with enduring national policies initiated in the early twentieth century and intensified during the 1960s [13]. Significantly, the land was initially pristine, representing an untouched desert without any prior agricultural cultivation. The amelioration and rehabilitation of sandy soils present a prolonged process, requiring several years for fertility improvement. Despite subsequent crop cultivation, the soil maintains deficiencies in humus content with low cation exchange capacity and limited concentrations of macro- and micronutrients.

Plant cultivation in newly reclaimed sandy lands is marred by substantial environmental stresses that detrimentally impact productivity and quality. These challenges stem primarily from the distinct characteristics of such lands. Sandy soils, characterised by their limited water-holding capacity, give rise to water scarcity issues, thereby subjecting plants to drought stress. Furthermore, these soils frequently exhibit deficiencies in essential nutrients, subjecting plants to nutrient deficiency stress. Additionally, the pronounced temperature fluctuations between day and night can induce thermal stress, adversely affecting the growth and development of plants. It is predicted that climate change will complicate the situation.

To tackle this problem, we need an uncomplicated and beneficial tool. GA3 has shown promise in enhancing plant tolerance to abiotic stresses in newly reclaimed sandy lands. Jianjun et al. [14] found that GA3 is essential for plants to cope with environmental stress. For instance, it improves plant adaptability to low light stress by regulating key processes such as photosynthesis, ROS metabolism, and protection mechanisms. It also helps in the expression of crucial genes in maize. Moreover, Khan et al. [15] indicated that GA3 can modulate oxidative stress processes and enhance antioxidant enzyme activity, consequently suppressing the negative effect of abiotic stress. Furthermore, exogenous GA upregulated the glyoxalase system, which had a crucial effect in assisting the survival of wheat seedlings under drought stress conditions [16]. Wang et al. [17] reported that low exogenous GA3 levels could decrease the endogenous GA content and elevate the ABA/GA ratio and soluble protein content, which helps to improve the wheat plants' cold tolerance. They indicated the importance of endogenous GA metabolism and ABA/GA balance in exogenous GA3-mediated cold tolerance. Jianjun et al. [14] experimented on two types of maize plants—SN98A and SN98B—to see how exogenous GA3 would affect them under low light conditions. Treated with GA3, SN98A showed a significant decrease in the barren stalk ratio and increased the seed setting rate, net photosynthesis, transpiration, stomatal conductance, photosynthetic pigments, photochemical efficiency, and antioxidant enzyme activities. All of these results showed the positive effects of exogenous GA3 application in combatting environmental stresses. Concerning tolerance to heat stress, only a few reports are available to clarify the vital roles of GAs in high-temperature stress responses and adaptation, especially at the reproductive stage [18].

This study aimed to explore the practicality of applying exogenous GA3 to enhance plant tolerance to environmental stresses in newly reclaimed arid lands. We hypothesised that GA3 could positively impact Cape gooseberry plant growth, enabling them to adapt to these harsh conditions and produce higher yields. Specifically, this study aimed to assess the effects of various GA3 concentrations on the growth, yield, and quality of plants cultivated in newly reclaimed arid lands, with the ultimate goal of determining the optimal level to address the challenges posed by such conditions.

2. Materials and Methods

Seeds of Cape gooseberry (*Physalis peruviana* L.), cv. 'Balady', the local cultivar in Egypt, were sown in the 2nd week of March 2019. The fruits of this local cultivar are relatively smaller, sweeter, and tastier than those from the imported cultivars. Cape gooseberry was chosen for its high value and nutritional richness, making it an essential crop in Egyptian markets. The crop's sensitivity to adverse conditions further justifies the choice, making Cape gooseberry an ideal subject for investigating adaptive and resilient agricultural practices.

The experimental station of the National Research Centre is situated in the Nubaria region of Egypt, located to the west of the Nile Delta. Its latitude is 30°30′ N, and its longitude is 30°20′ E, with an elevation of 24 m above sea level. The regional area has an arid climate, hot and dry from May to October, and cold for the remaining months, with a long-run average seasonal rainfall of 25 mm, mainly between November and March.

The experimental site featured sandy soil, characteristic of newly reclaimed land in the region, with a deep profile and adequate drainage. It comprises 85.5% sand, 11.7% silt, and 2.8% clay. The alkaline pH of the soil was 8.2, with an EC of 0.85 dS m^{-1} and 1.5% $CaCO_3$ content. The soil's field capacity was constrained, featuring rapid hydraulic conductivity and faster infiltration rates.

The seeds were meticulously sown in trays filled with a carefully prepared growth medium comprising a 1:1 ratio of peat moss and sand. This growth medium was chosen for its well-established properties in providing optimal support for seed germination and early seedling development. Peat moss contributes to water retention and aeration, fostering favourable conditions for root development, while the addition of sand ensures proper drainage and prevents compaction. The seedlings were placed in a nursery located *on-site* at the National Research Centre. This nursery environment provided the controlled conditions, including temperature and humidity regulation, essential for uniform germination and early seedling establishment.

After 40 days of sowing, selected seedlings, which had reached an appropriate developmental stage and demonstrated vigour and resilience, were carefully transplanted in the field. This deliberate approach aimed to ensure that the seedlings were robust before their introduction to the experimental field. The hills were placed 40 cm apart, with a distance of 1 m between the ridges. The agricultural experiment utilised a drip irrigation system to deliver water to the crops. Before crop planting, twin-wall GR drip tubing with a 15 mm inner diameter and 40 cm dripper spacing was positioned on the soil surface next to each plant row at the centre of the soil beds. The tubing operated at a pressure of 100 kPa and delivered 2.5 litres of water per hour. To determine the water requirements of the crops, the Penman–Monteith formula [19] was employed based on evapotranspiration replenishment. The crops were irrigated every other day to meet their water needs. Forty days after transplanting, the plants received two applications of GA3 at varying concentrations (100, 150, 200, and 250 ppm), in addition to a control treatment consisting of plants sprayed with water only.

The experimental design used in this study was a complete randomised block design with four replicates. The study employed a comprehensive set of methodological approaches to assess various aspects of plant growth, fruit yield, and physiological parameters. Below is an extended explanation of each parameter and the methods used.

2.1. Measurements of Vegetative Growth and Yield

For each treatment group, 12 representative plants were selected to assess the vegetative growth and yield characteristics. This sample size helps to ensure statistical reliability. The measurements were taken 90 days after transplanting, a crucial stage in the development of Cape gooseberry plants.

Three essential parameters were recorded:

1. The plant height, an indicator of plant growth, was measured from the base of the plant to the tip of the main stem.
2. The number of branches, as an indicator of plant branching and canopy development, which can influence fruit production.
3. The fresh weight of the entire plant (g/plant), which provides insight into the overall plant size and vitality.

Furthermore, Cape gooseberry fruits were collected at the harvest stage every week to assess three fruit-related parameters:

1. The total number of fruits, which reflects the fruit production capacity of the plants.
2. The fresh weight of fruits, which provides valuable data on fruit size and overall yield.
3. The fruit diameter, as a factor in evaluating fruit quality and marketability.

2.2. Total Soluble Solids (TSS)

This parameter was determined using a portable refractometer, specifically the Brixstix BX 100 Hs model from Techniquip Corporation, Livermore, CA, USA, which was used to assess the quality and taste of Cape gooseberry fruit.

2.3. Total Chlorophyll Content

The chlorophyll content in the third fully expanded leaf was quantified using a Minolta SPAD-501 chlorophyll meter from Minolta Co. Ltd., Tokyo, Japan. The readings obtained from the chlorophyll meter were immediately recorded as digital values. This device measures SPAD units, which is an indirect way to estimate the chlorophyll content and, consequently, the photosynthetic activity of the plants. It indicates the plant's ability to convert light energy into chemical energy.

2.4. Relative Water Content

The RWC of the third fully expanded leaf was measured according to the method outlined by Turner [20]. RWC is a critical parameter for assessing the water status of the plants. It provides insight into the plant's water retention and hydration, which is vital for overall health and growth.

2.5. Leaf Temperature

The leaf temperature measurements were acquired using an infrared thermometer, specifically the DT 8500 from Cheerman, Shenzhen, China, known for its efficiency in capturing data swiftly. This technology minimises susceptibility to environmental variations, even in dynamic field conditions. We conducted temperature measurements of the third fully expanded leaves, intentionally avoiding those directly exposed to sunlight. These measurements were conducted in August at midday. Monitoring the leaf temperature can indicate stress or physiological changes in the plant. It can also provide insights into the plant's response to environmental conditions, such as heat stress.

Collectively, these methodological approaches provide a comprehensive understanding of the growth, fruit yield, physiological status, and environmental response of Cape gooseberry plants. Combining these parameters allows for a thorough assessment of the plant's overall health and productivity.

2.6. Statistical Analysis

The analysis of variance was calculated according to Gomez and Gomez [21]. The Tukey test at a 5% significance level was used to compare the means.

3. Results and Discussion

3.1. Effects of GA3 Levels on Plant Growth Parameters, Yield, and Fruit Characteristics

Cape gooseberry fruits (*Physalis peruviana* L.) are produced inside a so-called papery husk. Figure 1 shows the vegetative growth, seeds, and fruits of Cape gooseberry plants grown under the experimental conditions of the Nubaria region.

Figure 1. The image displays the Cape gooseberry 'Balady', a local Egyptian variety, in various stages of development. The plants were cultivated in sandy soil in the Nubaria region to the West of the Nile Delta. The picture on the right-hand side shows the small fruits with a papery husk and a 1–2 cm diameter.

Cape gooseberry plants cultivated in newly reclaimed land responded positively to GA3, as indicated by plant height, number of branches, and plant fresh weight (Table 1). Interestingly, when GA3 application levels were between 100 and 150 ppm, there was no significant difference in the number of branches observed. It has been reported that gibberellic acid (GA3) is indispensable in plant growth. Qian et al. [22] emphasised the pivotal role of gibberellins in plant growth facets, encompassing cell elongation, cell expansion, and xylem differentiation. Their research revealed that exogenous GA3 application significantly promoted xylem development in both stem and root tissues. According to Singh and Lal [9], exogenous GA3 accelerates the rates of cell division and cell elongation rates at the sub-apical meristem. Subsequently, it enhances tomato plant growth and the quality of fruits. Our study demonstrated that the optimal level of performance was achieved at a concentration of 200 ppm.

Understanding the molecular mechanism of gibberellic acid (GA) movement within plant cells remains a challenging effort, as the precise mechanisms governing GA's roles in various aspects of plant growth and development, such as floral development, sex expression, development, and seed germination, remain enigmatic [23]. Gupta and Chakrabarty [23] noted that GA stimulation is linked to diverse processes, including seed germination, transitions from meristem to shoot growth, shifts from juvenile to adult leaf stages, transitions from vegetative to flowering phases, and the determination of sex expression. These effects are intricately intertwined with environmental factors, such as light, temperature, and water availability. The authors underscored the significance of comprehending GA transport mechanisms for plant species' survival and successful crop production.

Table 1. Effects of different levels of GA3 on vegetative growth characteristics of Cape gooseberry plants.

Treatments	Plant Height (cm)	Number of Branches (per Plant)	Fresh Weight (g/Plant)
GA (100 ppm)	83.8 c	16.1 c	511.9 d
GA (150 ppm)	96.2 b	16.5 bc	634.2 c
GA (200 ppm)	111.3 a	22.5 a	990.2 a
GA (250 ppm)	106.1 a	18.3 b	663.7 b
Control	65.6 d	14.6 d	427.3 e

Means with the same letter are not significantly different at 5%, according to the Tukey test.

3.2. Effects of GA3 Levels on Total Chlorophyll Content, Relative Water Content, and Leaf Temperature of Cape Gooseberry Leaves

An increase in the GA3 concentration positively affected the chlorophyll content of leaves (Table 2). According to Khangjarakpam et al. [24], GA3 has a beneficial impact on the chlorophyll content of African marigold plants by improving the biochemical constituents of their leaves. This is achieved by reducing the activity of the chlorophyllase enzyme, as previously reported, which slows down the process of chlorophyll degradation and increases the rate of photosynthesis and the size of the leaf surface area [25]. Similarly, El-Tohamy et al. [12] found that GA3 positively increased the chlorophyll content of Cape gooseberry plants. In the present study, while GA3 increased the chlorophyll content compared to the control, there were no significant differences among the levels of 100, 150, and 250 ppm.

Table 2. Effects of different levels of GA3 on total chlorophyll content, relative water content, and leaf temperature of Cape gooseberry plants.

Treatment	Total Chlorophyll Content (SPAD)	Relative Water Content (%)	Leaf Temperature (°C)
GA (100 ppm)	34.08 b	68.38 c	34.35 ab
GA (150 ppm)	35.05 b	73.88 ab	34.28 ab
GA (200 ppm)	38.50 a	74.75 a	33.90 b
GA (250 ppm)	35.75 b	71.38 b	34.08 b
Control	31.13 c	67.25 c	34.88 a

Means with the same letter are not significantly different at 5%, according to the Tukey test.

The RWC in leaves is an essential indicator of a plant's water status. Enhancing the water status of plants is intricately connected to maintaining optimal levels of photosynthesis and other essential metabolic processes. According to our study, the RWC can be significantly improved by applying GA, particularly at 150–200 ppm (Table 2). A recent study by Islam et al. [26] found that the exogenous application of GA3 positively impacted the RWC in the leaves of Mung bean (*Vigna radiata*) varieties. The researchers observed that the application of GA3 increased the RWC compared to a control, and the highest RWC (85.52% and 88.35%) was recorded with the application of 200 ppm of GA3 in BARI Mung-6 and BARI Mung-8, respectively. Furthermore, the application of GA3 appeared to improve root growth, which could help the plants increase water uptake. The study also showed that the exogenous application of GA3 led to decreased stomatal resistance and increased water use efficiency in tomato plants [27].

Through our study, we found that applying GA3 to plants resulted in improved water uptake. As a result of the enhanced water absorption, the temperature of the GA3-treated plants showed a tendency to be lower with applications of 100–150 ppm and significantly lower with applications of 200–250 ppm than that of the control (Table 2). Leaf or canopy temperatures can be used as a fast, cheap, and non-destructive screening tool for estimating stress tolerance, such as drought tolerance, among different plants, including maize [28] and rice [29]. Talebi [30] conducted a study on the effect of drought stress on the canopy temperature and total chlorophyll content of durum wheat. The study found that the genotypes with high yields in well-watered conditions also had a low canopy temperature and high chlorophyll content. The study concluded that wheat genotypes with a low canopy temperature can maintain high transpiration and photosynthetic rates and produce high yields under moisture-stressed conditions [30]. Correspondingly, this elucidates why, in our study, the leaf temperatures were below 35 °C, i.e., lower than the concurrent air temperature of 37 °C, as transpiration distinctly governs leaf cooling. Significantly, these measurements were undertaken at midday, and the plants demonstrated a well-watered status.

3.3. Effects of GA3 Levels on Plant Generative Development Parameters—Yield, Fruit Characteristics, and Total Soluble Solids of Fruits

In our study, the application of GA3 resulted in a significant improvement in plant generative development, leading to increased fruit number, fresh fruit weight, and fruit diameter (Table 3). We observed a clear dose-dependent response to GA treatment, where increasing the concentration of GA3 resulted in improved fruit parameters. The best results were achieved at a GA3 concentration of 200 ppm. For instance, the number of fruits per plant increased from 47.7 in the control to 136.3 when 200 ppm GA3 was applied. Similarly, the fruit weight per plant substantially increased from 71.8 g in the control treatment to 215.2 g in the 200-ppm treatment. Qian et al. [22] indicated that exogenous GA3 application induced alterations in the transcript levels of genes involved in the GA biosynthetic pathway, GA signalling, and genes related to auxin, cytokinin, and secondary cell wall biosynthesis. This suggests that GAs may interact with other hormones, such as auxin and cytokinin, to modulate the expression of genes related to secondary cell wall biosynthesis and trigger xylogenesis in eucalyptus plants. Our results are consistent with those of Kaur et al. [1], who demonstrated the significant impact of GA3 on enhancing the size and weight of Cape gooseberry fruits. Furthermore, Singh et al. [31] reported that applying GA3 during different stages, such as vegetative, flowering, and fruit-setting, significantly improved the yield of Cape gooseberry fruits.

Table 3. Effects of different levels of GA3 on the number of fruits, fruit weight, fruit diameter, and total soluble solids of fruits.

Treatment	Number of Fruits (per Plant)	Fruit Weight (g/Plant)	Fruit Diameter (cm)	Total Soluble Solids of Fruits
GA (100 ppm)	52.6 d	92.1 d	1.5 c	11.2 cd
GA (150 ppm)	117.5 b	197.7 b	1.6 c	12.2 bc
GA (200 ppm)	136.3 a	215.2 a	1.9 a	13.5 a
GA (250 ppm)	92.8 c	170.7 c	1.7 b	12.6 ab
Control	47.7 e	71.8 e	1.3 d	10.5 d

Means with the same letter are not significantly different at 5%, according to the Tukey test.

Moreover, tendentially, three levels of GA3 (150, 200, and 250) significantly increased the total soluble solids (TSS) in fruits, suggesting an improvement in fruit quality (Table 3). Kumar et al. [11] reported similar results showing the enhancing effect of GA3 on the TSS of Cape gooseberry fruits. Further, Kumar et al. [3] found that spraying GA3 enhanced TSS, reduced sugar and total sugar content, and decreased the acidity of Cape gooseberry fruits. The authors attributed this effect to the PGR's ability to accelerate biochemical reactions, increasing TSS content. In addition, Singh et al. [31] reported a noteworthy elevation in total soluble solids (TSS) in Cape gooseberry fruits following the application of GA3 foliar spray, compared to the control. The authors attributed this significant change to the higher accumulation of sugars and other soluble compounds or the faster conversion of starch and acids into simple sugars. Kaur et al. [1] also reported that GA3 enhanced TSS, reduced sugars, and minimised the acid content of Cape gooseberry fruits. The increase in sugar content with gibberellins is due to their role in the synthesis of α-amylase, which converts starch into reducing sugars. The decreased acidic content and increased sugar level make Cape gooseberry fruits taste sweeter, making them more appealing to consumers.

Summarising the findings, cultivating Cape gooseberry cv. 'Balady' in sandy soils in newly reclaimed lands exposes them to various abiotic stresses that can adversely affect their productivity and growth. By modulating gene expression, the exogenous application of GA3 can enhance crop plants' metabolic processes, yield, and quality components [8]. Our current findings are a critical step, providing a detailed examination of the effects of GA3 on cv. 'Balady', a well-known local cultivar in Egypt. Subsequent research efforts can build upon our work to encompass a broader spectrum of cultivars, ensuring a more holistic understanding of the application of GA3 across the entire cape gooseberry species.

Due to the prediction of worsening climate conditions in this area caused by advanced climate change [32,33], it is crucial to explore the use of these applications in combination with other phytohormones [8] and smart agro-practices [34] for managing abiotic stress in arid regions [35] in the future.

4. Conclusions

Cape gooseberry plants cultivated in sandy soils in newly reclaimed lands are frequently subjected to various environmental stressors, which can lead to suboptimal productivity and quality. However, our study indicated that applying gibberellic acid (GA3) can significantly enhance the growth and yield of these plants in arid regions, such as the West Delta region of Egypt. GA3 was found to augment growth, increase the chlorophyll content in leaves, improve water status, boost productivity, and elevate the total soluble solids in Cape gooseberry fruits. The higher concentrations of GA3 (200 and 250 ppm) achieved the most pronounced effects, with superiority of the level of 200 ppm in most parameters. This application could also be recommended from an economic standpoint. Based on our findings, the application of GA3 emerges as a practical and cost-effective solution for farmers, demonstrating its effectiveness in enhancing the growth, yield, and quality of Cape gooseberry plants in arid zones. These promising outcomes underscore the potential of GA3 as a valuable tool for agricultural practices in challenging environments. However, further research is needed to understand the mechanism and explore the role of gibberellins in managing abiotic stress as a viable strategy to mitigate adverse environmental conditions in arid regions. Moreover, investigating GA3 application under various irrigation levels becomes crucial to assessing its effectiveness in addressing drought conditions. This nuanced examination will offer critical insights into the adaptability and potential limitations of GA3 application, providing valuable information for diverse climate change scenarios.

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