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EFECTO EN LA CALIDAD NUTRICIONAL DEL FRUTO DE TOMATE (*Solanum lycopersicum* L.) CON APLICACIONES DE YODO (I) Y SELENIO (Se)

Tesis

Que presenta FERNANDO MEJÍA RAMÍREZ

como requisito parcial para obtener el Grado de

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Tesis

Elaborada por FERNANDO MEJÍA RAMÍREZ como requisito parcial para obtener el grado de Doctor en Ciencias en Agricultura Protegida con la supervisión y aprobación del Comité de Asesoría

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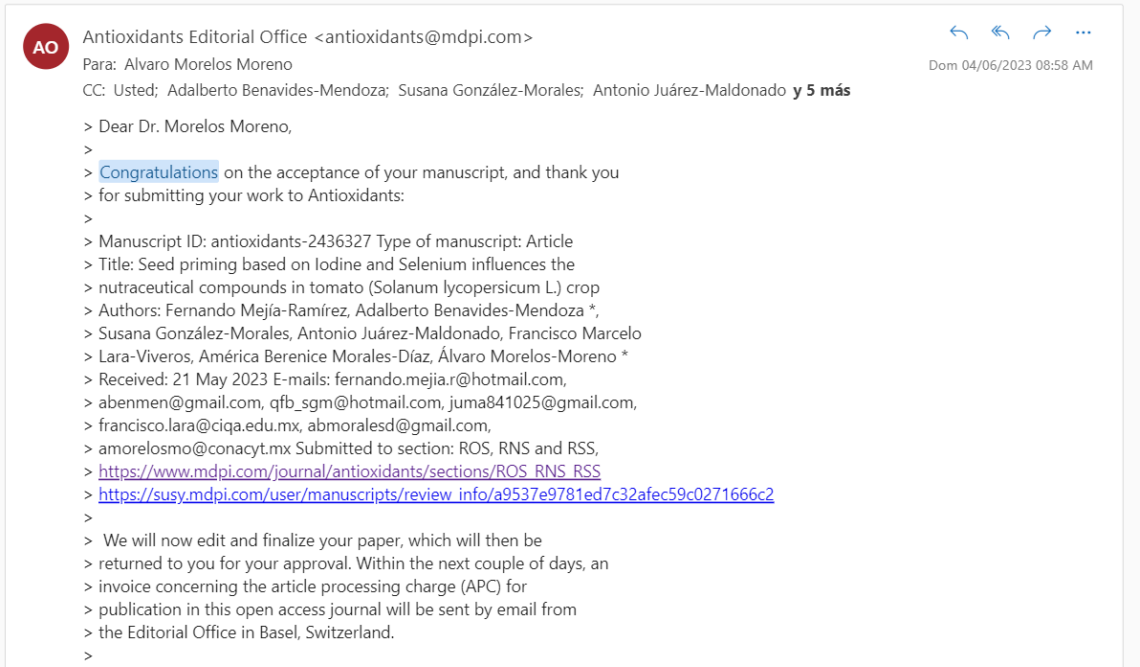

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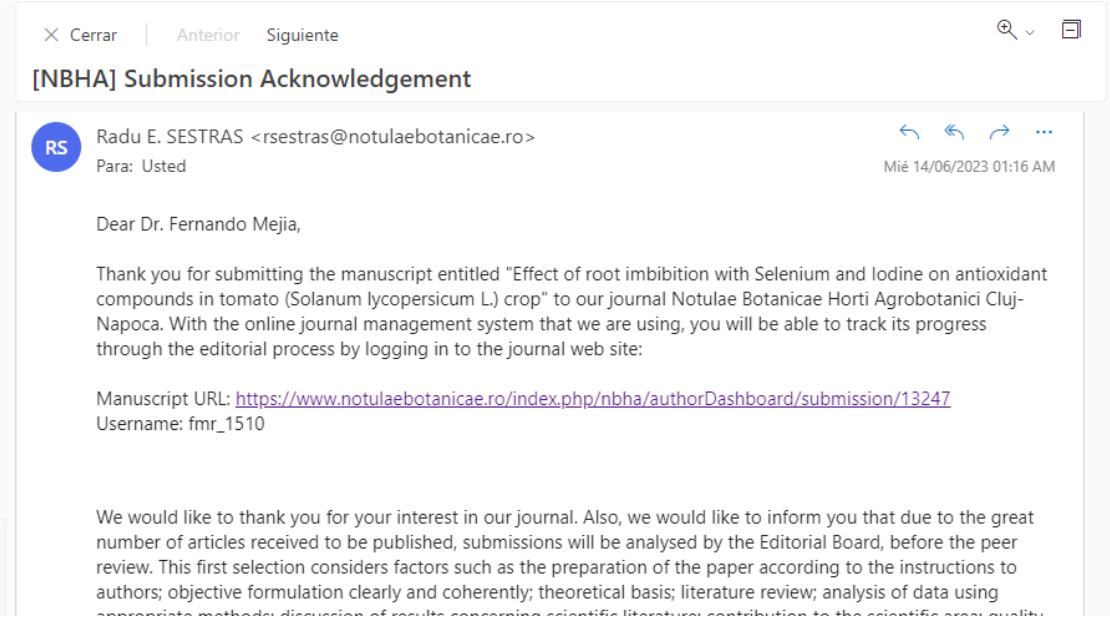

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Dear Dr. Fernando Mejia,

Thank you for submitting the manuscript entitled "Effect of root imbibition with Selenium and Iodine on antioxidant compounds in tomato (Solanum lycopersicum L.) crop" to our journal Notulae Botanicae Horti Agrobotanici Cluj-Napoca. With the online journal management system that we are using, you will be able to track its progress through the editorial process by logging in to the journal web site:

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INTRODUCCIÓN

El consumo insuficiente de micronutrientes como el yodo (I) y selenio (Se) a través de los alimentos es limitado lo que puede causar una mala nutrición, y se ve reflejado en el desarrollo y crecimiento de los humanos, el yodo y selenio, son elementos que se requieren en pequeñas cantidades, pero son de gran importancia para el funcionamiento adecuado de la glándula tiroidea, se ha demostrado estar asociada a la carcinogénesis y su tratamiento en diversas líneas celulares, actuando como antioxidante y como antiproliferativo (Aceves *et al*., 2005; Avery y Hoffmann, 2018; Guillin *et al*., 2019).

La aplicación de elementos como el yodo y el selenio en las plantas de cultivo, con el fin de corregir la deficiencia de elementos esenciales en la dieta humana ha tomado importancia nivel mundial, además, el uso de estos elementos en la agricultura presenta aspectos interesantes, debido a que estos elementos en las plantas puede favorecer el crecimiento y el potencial de tolerancia al estrés, cuando se aplica en concentraciones bajas (Hasanuzzaman *et al*., 2010).

El yodo y selenio juegan un papel importante en el beneficio a plantas de cultivo, el selenio es considerado un bioestimulante, presentando efectos positivos, en el crecimiento y desarrollo del cultivo, donde su uso en los cultivos presenta una disminución en el contenido de H_2O_2 y O_2^- (Zhu *et al*., 2017), lo que indica que el selenio tiene un efecto en la activación del sistema de defensa para controlar la producción y acumulación de especies reactivas de oxígeno (ERO), para esto el sistema de las células vegetales aumentan los niveles de metabolitos antioxidantes no enzimáticos, incluidos el glutatión, el ascorbato y el tocoferol, y una amplia red de antioxidantes enzimáticos, como las superóxido dismutasas, catalasas, ascorbato peroxidasas y glutatión reductasas, entre otros (Mittler *et al*., 2004).

El uso de estos elementos se consideran elementos beneficiosos, mas no esenciales, sin embargo, el selenio es catalogado como un bioestimulante vegetal inorgánico, debido a que ha demostrado una mejora en la absorción de nutrientes, aumenta la tolerancia de las plantas al estrés y mejora la calidad del rendimiento de los cultivos (Dima *et al*., 2020; Hasanuzzaman *et al*., 2020; de Mello Prado, 2021) debido a que en bajas concentraciones pueden funcionar como señalizadores para mejorar el sistema de defensa de la planta lo

que se refleja en un incremento en el contenido de metabolitos secundarios; sin embargo, en altas concentraciones puede provocar daño oxidativo en los tejidos (Mittler, 2017; Abedi *et al*., 2021). Por su parte el tomate (*Solanum lycopersicum* L.) es uno de los cultivos de mayor importancia en México y el mundo, tanto por su importancia económica como por ser un alimento rico en vitaminas, minerales y antioxidante, al ser consumidos como vegetales frescos, ya sea crudos o cocidos, son una fuente importante de carotenoides y otros nutrientes que promueven la salud en la dieta humana (Meng *et al*., 2022). Por tal motivo se planteó el objetivo de evaluar el efecto de aplicación de yodo y selenio con aplicaciones en imbibición de semilla, imbibición de raíz y aspersión foliar sobre los indicadores nutraceúticos y de capacidad antioxidante en frutos y hojas de tomate.

REVISIÓN DE LITERATURA

Imbibición

El proceso de germinación se ve afectado por factores externos como el tiempo de germinación y la ausencia o presencia de luz, los cuales pueden ayudar o inhibir la germinación en relación con la reserva (contenido nutricional) dentro de la semilla. Durante la germinación, algunas reservas de la semilla se degradan y se utilizan para la respiración y la síntesis de nuevos constituyentes celulares para el embrión en desarrollo, lo que provoca cambios significativos en las características bioquímicas, nutricionales y sensoriales (Kim *et al*., 2012).

La imbibición es un proceso efectivo y común, utilizado para mejorar la calidad nutricional, asegura una mayor germinación y uniforme, al reducir el tiempo de germinación, aumenta la activación de enzimas pre-germinativas, producción de metabolitos, repara el ADN dañado y regula la ósmosis (Damaris *et al*., 2019). El "Seed priming" es considerada una técnica a base de agua que permite la hidratación controlada de la semilla para desencadenar el metabolismo pregerminativo, pero no permite que emerja la radícula (Dutta, 2018).

La germinación de semillas no latentes tiene lugar en tres etapas, cuando la semilla reúne condiciones de crecimiento favorables se inicia el proceso de la germinación dividida en tres fases (Khan *et al*., 2022):

(I) Imbibición: inicia con una gran absorción de agua por parte de la semilla seca, lo que permite que las células de la semilla se hidraten, la semilla absorbe el máximo de agua para activar la vía de señalización del ácido giberélico (GA) y los factores de transcripción de las enzimas hidrolíticas, como la *a*-milasa que inician la descomposición del almidón en azúcares simples. Ambos procesos promueven la descomposición de los materiales del endospermo y proporcionan azúcar soluble para iniciar el proceso de germinación.

(II) Fase de latencia: En esta fase existe un incremento en el contenido de ADN, síntesis de proteínas donde participan los ARNm.

(III) Protrusión de la radícula a través de la cubierta seminal a lo que llamamos una semilla germinada.

La absorción de agua durante la etapa de preparación de semillas es fundamental para la germinación y crecimiento de plántulas, y estas características tienen implicaciones agronómicas prácticas, al mejorar la germinación, velocidad de germinación, vigor en plántulas, longitud de raíces y el contenido de materia seca, eficiencia fotosintética, además de mejorar el estado bioquímico de la planta, al presentar una mayor actividad de la *a*-amilasa y el contenido carbohidratos solubles dúrate la germinación de la semilla (Siddique y Bose, 2007; Bose *et al*., 2018; Marthandan *et al*., 2020). El proceso de germinación da como resultado una serie de cambios bioquímicos en el interior de la semilla y la acumulación de diversos fitoquímicos (Cáceres *et al*., 2014).

La imbibición de semillas actúa como una exposición al estrés previa a la germinación y crea una "memoria de estrés" en las células que facilita la expresión de respuestas de estrés en exposiciones posteriores (Paparella *et al*., 2015), desde este punto de vista, la imbibición es similar al fenómeno de aclimatación durante la imbibición temprana de semillas (Amooaghaie y Tabatabaie, 2017)

La imbibición con nutrientes se ha propuesto como una técnica novedosa que combina los efectos positivos de la imbibición de semillas con un suministro mejorado de nutrientes. Las semillas se pre-tratan en soluciones que contienen los nutrientes limitantes en lugar de remojarlas solo en agua (Arif, 2005). La creciente evidencia sugiere que el estado de los nutrientes minerales de las plantas juega un papel crítico en el aumento de la resistencia de las plantas a los factores de estrés ambiental (Jisha *et al*., 2013).

Existen diferentes técnicas de imbibición de semillas, como es el hidropriming, el cual consiste en poner la semillas en una solución a base agua pura, por su parte el osmopriming consiste en someter a las semillas en una solución osmótica, donde se han utilizado amplios compuestos como NaCl, KCl, KNO_3, K_3PO_4 , KH_2PO_4, $MgSO_4$ y $CaCl_2$, donde se ha establecido que dicha técnica promueve la tolerancia a la salinidad, aumento de la productividad, germinación, mejora la calidad de la semilla, reduce las aplicaciones de los

fertilizantes, inducción a resistencia de enfermedades y tolerancia a sequía (Singh *et al*., 2020).

El uso de tratamientos de imbibición u osmopriming, se ha establecido como un método efectivo para mejorar la respuesta de las plantas a condiciones de estrés biótico y abiótico, mediante la alteración del metabolismo antioxidante (Kumar *et al*., 2016), estimula el sistema antioxidante al mejorar la actividad enzimática como: superóxido dismutasa (SOD), ascorbato peroxidasa (APX), catalasa (CAT), y compuestos no enzimático como: glutatión reducido (GSH), ácido ascórbico (AsA) y compuestos fenólicos (Anaytullah y Bose, 2012; Paparella *et al.*, 2015). Los sistemas antioxidantes de las plantas eliminan la producción excesiva de especies reactivas de oxígeno (ERO) provocada por diversos tipos de estrés y desempeñan un papel importante durante el almacenamiento, la germinación y desarrollo de las semillas, este sistema antioxidante está compuesto tanto enzimáticos como no enzimáticos, donde sirven a la planta para reducir el nivel de las ERO, donde la catalasa degrada el H_2O_2 en oxígeno y agua, mientras que el ascorbato peroxidasa utiliza el ácido ascórbico como donante de electrones para estimular la degradación del H_2O_2, mientras que el glutatión reducido es responsable de la producción del ácido ascórbico (Hussain *et al*., 2019). El glutatión reductasa cataliza la regeneración de glutatión reducido (GSH) a partir de glutation oxidado (GSSG), con NADPH como agente reductor. GSH elimina H_2O_2 al reaccionar de forma no enzimática con O_2^- , OH^-, así mismo el GSH, tiene la capacidad de reponer ácido ascórbico, a través del ciclo de ascorbato-glutation, el cual es de gran importancia para el sistema antioxidante (Millar *et al*., 2003)

Elementos esenciales

Hasta el momento, se ha demostrado que 16 elementos son esenciales para el crecimiento y el desarrollo de las plantas superiores según los criterios de esencialidad establecidos por (Arnon y Stout, 1939)

Criterios de esencialidad:

- La deficiencia de algún elemento, imposibilita que la planta complete su etapa vegetativa y reproductiva en su ciclo de vida
- La deficiencia de dicho elemento puede prevenirse o corregirse únicamente con el suministro de dicho elemento

- El elemento debe estar involucrado directamente en el metabolismo de la planta

Sin embargo, el uso de elementos como el yodo (I) y selenio (Se), son considerados elementos beneficiosos, mas no esenciales, El selenio es catalogado como un bioestimulante vegetal inorgánico, debido a que ha demostrado una mejora en la absorción de nutrientes, aumenta la tolerancia de las plantas al estrés y mejora la calidad del rendimiento de los cultivos (Dima *et al*., 2020). Las plantas tienen la capacidad de absorber elementos químicos en el suelo o la solución de nutritiva con poca restricción, que podría ser un nutriente, nutrientes no minerales de la atmósfera o un elemento beneficioso y/o tóxico (Kathpalia y Bhatla, 2018), los elementos benéficos podrían ser considerados esenciales. Asimismo, algunos de los elementos benéficos son esenciales para ciertas familias o grupos de plantas, en esta clasificación se encuentra al aluminio (Al), cesio (Ce), cobalto (Co), lantano (La), sodio (Na), selenio (Se), silicio (Si), titanio (Ti), vanadio (V) y yodo (I) (Trejo-Téllez *et al*., 2007)

Además de los elementos considerados esenciales para la vida vegetal, existen elementos considerados beneficiosos y también un grupo de elementos tóxicos. El elemento benéfico se define como aquel que estimula el crecimiento de las plantas, pero no es esencial o es esencial solo para ciertas especies o bajo ciertas condiciones(de Mello Prado, 2021). El silicio, el cobalto y el selenio se consideran beneficiosos para el crecimiento de ciertas plantas. (Trejo-Téllez *et al*., 2007). Por su parte el yodo no se ha demostrado como un elemento esencial para las plantas terrestres (Cakmak *et al*., 2017), sin embargo, se sabe que las plantas lo absorben por las raíces y las hojas y lo disipan a la atmósfera en forma gaseosa utilizando metiltransferasas de halógeno no dependientes del vanadio (Landini, 2011), por lo que es posible que el yodo realice funciones metabólicas aún no bien comprendidas en las plantas terrestres (Gonzali *et al*., 2017)

Selenio

El selenio (Se) es un micronutriente esencial para animales y humanos, aún no se ha establecido su esencialidad en las plantas. Sin embargo, juega un papel importante con beneficio en plantas de cultivo, particularmente bajo estrés biótico y abiótico. El selenio adopta vías de absorción y transporte en plantas similares a las del sulfato y/o fosfatos; puede reemplazar el azufre a nivel celular para sintetizar macromoléculas importantes,

incluidos aminoácidos, proteínas estructurales y funcionales específicas y/o proteínas no específicas potencialmente tóxicas y otros seleno-compuestos (Sarwar *et al*., 2020).

Las raíces de las plantas adquieren el selenio de la solución de la rizosfera, se pueden absorber como selenato (SeO_4^{2-}), selenito (SeO_3^{2-}) y compuestos de organoselenio, como seleniocisteína (SeCys) y seleniometionina (SeMet), pero no se pueden absorber seleniuros o Se elemental (White, 2018). Las plantas son capaces de absorber iones de selenato y selenito en la raíz; sin embargo, ninguno de los iones se absorbe a través de un transportador específico de Se. El selenato se absorbe a través de los simportadores H^+/sulfato, los SULTR 1;1 y SULTR 1;2, son transportadores de alta afinidad, funcionan para absorber el sulfato en la raíz, sin embargo, se ha demostrado que ambos trasportadores son capaces de trasportar selenato, mientras que el selenito es absorbido por los transportadores de fosfato inorgánico (Pi) y las acuaporinas (Schiavon y Pilon-Smits, 2017; White, 2018; Trippe y Pilon-Smits, 2021)

La comprensión actual del metabolismo del Se en las angiospermas se basa en gran medida en el conocimiento del metabolismo del azufre (S) (White, 2016; Schiavon y Pilon-Smits, 2017). Los aspectos del metabolismo del Se ocurren tanto en el citosol como en los plástidos de las células de las hojas. Se cree que la mayor parte del selenato ingresa al citosol de las células de la hoja a través de transportadores SULTR en su membrana plasmática y luego es transportado al plástido por homólogos del transportador SULTR 3;1, que se encuentra en la membrana del cloroplasto (Cao *et al*., 2013).

La base bioquímica de la toxicidad del Se radica en el hecho de que el Se y el S son análogos químicos. Por lo tanto, selenato y selenita se asimilan a SeCys y SeMet. La sustitución de cisteína y metionina en las proteínas por SeCys y SeMet que puede provocar la pérdida de la funcionalidad de las proteínas, que a su vez, se atribuye a proteínas mal plegadas o malformadas (Van Hoewyk, 2013). Además, la interacción del Se con las proteínas puede conducir a la formación de selenotrisulfuros, enlaces selenilsulfuro y diselenuros (Ganther, 1999).

El selenio mejora el crecimiento de las plantas y el potencial de tolerancia al estrés de las plantas cuando se aplica en concentraciones más bajas (Hasanuzzaman *et al*., 2010). Asimismo, la preparación con selenio protege a las plantas del daño oxidativo

inducido por la temperatura al estimular el sistema de defensa antioxidante de las plantas (Chen y Sung, 2001), así mismo el uso de yodo y selenio en la imbibición de semillas, resulta un método viable, debido a que se puede llevar a cabo el enriquecimiento de los brotes con el uso de ambos elementos, sin embargo, la captación depende de la forma y/o combinaciones de los elementos (Jerše *et al*., 2017)

Yodo

Las plantas pueden absorber el yodo del suelo, donde las principales especies de yodo son; iones de yodo orgánico, yodato (IO_3) y yoduro (I^-), por su parte en la atmosfera se puede encontrar en forma gaseosa, en forma de yodo molecular (I_2) y el yoduro de metilo (CH_3I) (Medrano-Macías *et al*., 2016). Las plantas pueden absorber yodo del suelo a través de las raíces y de la atmósfera por medio de las hojas. El yodato puede reducirse a yoduro por reductasas específicas identificadas en las raíces (Kato *et al*., 2013) o, posiblemente por otras reductasas de plantas que usan IO_3 como sustrato alternativo.

Una vez dentro de la planta, el yodo se mueve principalmente por la ruta xilemática. La volatilización y emisión de yodo a la atmósfera como yoduro de metilo, se produce a través de una enzima haluro metiltransferasa (HMT) dependiente de adenosilmetionina S (Redeker *et al*., 2000; Itoh *et al*., 2009; Medrano-Macías *et al*., 2016). Se han elaborado algunas hipótesis con respecto a la absorción de yodo por la raíz y la subsiguiente carga del xilema en función de las afinidades químicas con otros halógenos, en particular el cloro u otros nutrientes (White y Broadley, 2009). Sin embargo, hasta la fecha no se han identificado transportadores de yodo en las plantas y no se conocen con precisión las formas de yodo que se mueven dentro de la planta ni las que se almacenan dentro de los tejidos.

Se sabe muy poco sobre la absorción y el transporte de yodo en las células vegetales, especialmente en el caso de la absorción de yodo en la hoja. Se sabe que el nitrato y el yodato son químicamente similares, y por lo tanto, pueden competir durante la absorción y el transporte en los sistemas biológicos (Cakmak *et al*., 2017). El nitrato y el yodato posiblemente comparten la misma proteína transportadora, lo que puede causar una inhibición competitiva de la absorción de yodato en las especies de fitoplancton marino si el nivel de nitrato es alto en el medio (De La Cuesta y Manley, 2009).

El yodo en la planta presenta un incrementó la producción de biomasa, la floración y también está presente en proteínas de raíces y brotes, y ayuda a modular la expresión de genes implicados en respuestas de defensa (Nascimento *et al*., 2022) además, se ha demostrado que el selenio (Se) y el vanadio promueven la absorción de yodo en las plantas (Smoleń *et al*., 2021).

PRIMER ARTÍCULO

Seed priming based on iodine and selenium influences the nutraceutical compounds in tomato (*Solanum lycopersicum* L.) crop.

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Seed Priming Based on Iodine and Selenium Influences the Nutraceutical Compounds in Tomato (*Solanum lycopersicum* L.) Crop

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Abstract: The use of trace elements in agriculture as a complement to crop fertilization programs is a practice that is gaining importance and relevance worldwide. Iodine and selenium perform essential functions in human health, related to the proper functioning of the thyroid gland, acting as antioxidants and antiproliferatives, and their limited intake through food consumption can cause malnutrition, reflected in the abnormal development and growth of humans. This research aimed to evaluate the nutraceutical quality of tomato (*Solanum lycopersicum* L.) in response to seed priming based on KIO_3 (0, 100, 150, 200, 250 mg L^{-1}) and Na_2SeO_3 (0, 0.5, 1, 2, 3 mg L^{-1}), performed by interaction from a 5^2-factorial design and by independent factors in a 24-h imbibition time. The tomato crop was established under greenhouse conditions in 10-L polyethylene containers containing peat moss and perlite 1:1 (v/v). Regarding non-enzymatic antioxidant compounds, lycopene, β-carotene and flavonoid contents in tomato fruits significantly increased with KIO_3 and Na_2SeO_3 treatments; however, vitamin C content was negatively affected. KIO_3 increased the phenol and chlorophyll-*a* contents of leaves. In relation to enzymatic activity, KIO_3 positively influenced GSH content and PAL activity in tomato fruits. KIO_3 also positively influenced GSH content in leaves while negatively affecting PAL and APX activities. Na_2SeO_3 favored GSH content and GPX activity in tomato fruits and leaves. Na_2SeO_3 negatively affected the antioxidant capacity of hydrophilic compounds by ABTS in fruits and leaves and favored hydrophilic compounds by DPPH in leaves. Seed imbibition based on KIO_3 and Na_2SeO_3 is a method that is implemented in the tomato crop and presents interesting aspects that favor the nutraceutical quality of tomato fruits, which may contribute to increasing the intake of these minerals in humans through tomato consumption.

Keywords: KIO_3; Na_2SeO_3; antioxidant; seed imbibition; tomato

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1. Introduction

Seed imbibition is considered a water-based technique that allows controlled hydration of the seed to trigger pregerminative metabolism but does not allow radicle emergence [1]. Seed imbibition is a common and effective process used to improve nutritional quality. The germination process is affected by external factors such as temperature, relative humidity, and light conditions, which can help or inhibit germination in relation to the nutritional reserve within the seed. During the germination process, some seed reserves are degraded

and used for respiration and the synthesis of new cellular constituents for embryonic development, which causes changes in biochemical and nutritional characteristics [2].

The seed imbibition process consists of dipping the seeds in a water solution for some time, or imbibition time, allowing partial hydration without the radicle emerging. When a dry seed is kept in water, the germination process of non-dormant seeds occurs in three phases: imbibition, the lag phase, and protrusion of the radicle through the testa [3,4]. Seed priming is an effective method to improve seed physiological quality through uniformity and germination percentage [5]. It stimulates pre-germination metabolic processes, reduces the physical resistance of the endosperm during imbibition, repairs membranes, influences the development of immature embryos, and leaches inhibitors [3,6]. Seedlings from seed imbibition emerge faster, grow more vigorously, and tolerate adverse conditions (Table S1) related to certain physiological, biochemical, cellular, and molecular changes [7–9].

Treatments based on seed priming have been established as an effective method to improve the response of plants to biotic and abiotic stress conditions through the alteration of antioxidant metabolism [10]. This technique also stimulates the antioxidant system by improving the activity of antioxidant enzymes [11,12]. The use of iodine (I) and selenium (Se) in agriculture has become very relevant and important worldwide. At low concentrations, these elements present stimulatory effects and can favor the growth and development of crops and increase the content of secondary metabolites and antioxidant enzymes; however, at high concentrations, these elements can cause toxicity to plants.

Se plays an important role in the benefit of crop plants and is considered a biostimulant that promotes positive effects on the growth and development of crops. Se in the plants influences the accumulation of enzymes such as superoxide dismutases, catalases, ascorbate peroxidases, and glutathione reductases [13,14], which control the antioxidant metabolites, the production, and accumulation of reactive oxygen species (ROS), and activate the defense system [13]. Iodine and selenium are highly important in human health. The intake of these trace elements through food consumption is limited, which can cause malnutrition reflected in the abnormal development and growth of humans. These elements, required in small quantities, fulfill essential functions in the proper functioning of the thyroid gland (Table S2), which has recently been shown to be associated with carcinogenesis and its treatment in various cell lines, acting as an antioxidant and as an antiproliferative [15–17].

Tomato (*Solanum lycopersicum* L.) is a horticultural crop of worldwide importance due to its wide consumption as a processed byproduct and fresh presentation. This research aimed to evaluate the effect of seed priming based on I and Se on the nutraceutical quality of tomato fruits and leaves.

2. Materials and Methods

2.1. Crop Establishment

The tomato crop was established in a tunnel-type greenhouse with a plastic cover and natural ventilation in the Horticulture Department at the Universidad Autónoma Agraria Antonio Narro, in Saltillo Mexico (25°21′ NL, 101°01′ WL, altitude 1743 m). The average environmental conditions in the greenhouse during the crop cycle were: air temperature of 20 °C, relative humidity of 34%, solar radiation of 735 W m^{-2} and photosynthetically active radiation of 568 µmol m^{-2} s^{-1}. Potassium iodate (KIO_3) (99%, Sigma Aldrich, St. Louis, MO, USA) and sodium selenite (Na_2SeO_3) (99%, Sigma Aldrich, St. Louis, MO, USA) were used as I and Se species, respectively. Saladette-type CID F1 (Harris Moran®, Davis, CA, USA) tomato seeds were primed in KIO_3 and Na_2SeO_3 solutions, and the seeds of the control treatment were primed in distilled water (Table 1) for a 24-h imbibition time (Figure S1). Then, the seeds were dried at room temperature for 48 h.

Table 1. Priming treatments in tomato seeds based on I and Se.

Variation Factor	Concentration (mg L^{-1})
KIO_3	0, 100, 150, 200, 250
Na_2SeO_3	0, 0.5, 1, 2, 3

25 treatments (5^2 factorial), n = 4 replications, 100 experimental units.

2.1.1. Preparation of KIO_3 and Na_2SeO_3 Treatments

A stock solution of potassium iodate (KIO_3) at a concentration of 1000 ppm was prepared. A mass of 168.59 mg of KIO_3 was gauged to 100 mL with distilled water. Dilutions of 2.5, 3.75, 5, and 6.25 mL of the stock solution were gauged to 25 mL with distilled water to obtain the treatments of 100, 150, 200, and 250 mg L^{-1}, respectively.

A stock solution of sodium selenite (Na_2SeO_3) at a concentration of 1000 ppm was prepared. A mass of 21.89 mg of Na_2SeO_3 was gauged to 100 mL with distilled water. Dilutions of 12.5, 25, 50, and 75 µL of the stock solution were gauged to 25 mL with distilled water to obtain the treatments of 0.5, 1, 2, and 3 mg L^{-1}, respectively.

2.1.2. Sowing and Planting

After the seed priming process, seeds were sown in polystyrene trays with peat moss and perlite 1:1 (v/v) as substrates. Seedlings were planted 35 days after sowing in 10-L plastic containers with peat moss and perlite 1:1 (v/v) as substrate. Tomato plants were arranged in the greenhouse in a randomized complete block design with a factorial arrangement of two factors (KIO_3 and Na_2SeO_3) and five levels (concentrations in mg L^{-1}) (Table 1). Fertilization consisted of Steiner-type nutrient solutions [18], diluted in drip irrigation. The same substrate and fertigation conditions were used in the control and KIO_3 and Na_2SeO_3 treatments to avoid another variation factor affecting the performance of the treatment.

2.1.3. Sampling

Samples of the leaves and ripe fruits of tomato plants were obtained 120 days after planting. Leaf samples were collected from the leaf tissue of fully extended young leaves from 12 plants with four replications. Samples for biochemical analysis were collected from five ripe fruits per treatment, with a uniform color and size corresponding to stage six of ripening [19]. Samples were stored at −80 °C, lyophilized in a 2.5 L FreeZone Benchtop Free Dry System freeze-dryer (LABCONCO, Kansas, MO, USA), and ground to a fine powder.

2.2. Non-Enzymatic Compounds

2.2.1. Vitamin C

The vitamin C content was determined by the 2,6-dichlorophenolindophenol titration method [20]. Here, 20 g of fresh fruit tissue was macerated by using a mortar and pestle with 10 mL of hydrochloric acid (2%), and 100 mL of distilled water was added and filtered with sterile gauze A 10-mL aliquot was taken and titrated with 2,6-dichlorophenolindophenol until a pinkish color was obtained (Equation (1)). The results were expressed in mg per 100 g of fresh tissue (mg 100 g^{-1} FW).

$$\text{Vitamin C} = \frac{\text{mL of 2,6-dichlorophenolindophenol} \times 0.088 \times \text{total volume} \times 100}{\text{aliquot volume} \times \text{sample weight}} \quad (1)$$

2.2.2. Total Phenols

Total phenolic compounds were determined using the Folin–Ciocalteu method from the extraction with water:acetone [21], made by adding 50 µL of the extract, 200 µL folin–ciocalteu reagent, 500 µL Na_2CO_3, and 5 mL distilled water to a test tube. The mixture was vortexed for 30 s and placed in a water bath at 45 °C for 30 min. The absorbance of the

mixture was read at a 750 nm wavelength. The results were expressed in mg of gallic acid equivalents per gram of dry tissue (mg GAE g^{-1} DW).

2.2.3. Total Flavonoids

Flavonoids were determined by the Dowd method, adapted by Arvouet–Grand et al. [22]. It was made by adding 2 mL of the extract and 2 mL of $AlCl_3$ (2%) methanolic solution to a test tube. The mixture was allowed to react for 20 min in the dark. The absorbance of the mixture was read at a 415 nm wavelength. The results were expressed in mg of quercetin equivalents per 100 g of dry tissue (mg QE 100 g^{-1} DW).

2.2.4. Chlorophyll

Chlorophyll content was quantified using the method proposed by Munira et al. [23]. Here, 1 g of fresh plant material was homogenized, and then 5 mL acetone (90%) was added. Additionally, 10 mg of magnesium carbonate (to protect and stabilize chlorophylls) was added, 2 mL of the extract was centrifuged at 9408× *g* for 5 min at 4 °C, and the supernatant was extracted. Chlorophyll-*a* and chlorophyll-*b* were quantified by reading the absorbances at 663 and 645 nm wavelengths, respectively. The results were computed (Equations (2)–(4)) and expressed in µg per gram of fresh tissue (µg g^{-1} FW).

$$\text{Chlorophyll-}a = 3.64 \times A_{645} + 25.38 \times A_{663} \quad (2)$$

$$\text{Chlorophyll-}b = 30.38 \times A_{645} - 6.58 \times A_{663} \quad (3)$$

$$\text{Total chlorophyll} = 34.02 \times A_{645} + 18.8 \times A_{663} \quad (4)$$

2.2.5. Lycopene and β-carotene

Lycopene and β-carotene contents were determined according to Nagata and Yamashita [24]. Here, 100 mg of lyophilized tissue was mixed with 2 mL of hexane:acetone (3:2) solution. An aliquot was taken from the supernatant and the absorbances at 453, 505, 645, and 663 nm wavelengths were read. The results were computed (Equations (5) and (6)) and expressed in mg per 100 g of dry tissue (mg 100 g^{-1} DW).

$$\text{Lycopene} = -0.0806 \times A_{453} + 0.372 \times A_{505} + 0.204 \times A_{645} - 0.0458 \times A_{663} \quad (5)$$

$$\beta\text{-carotene} = 0.452 \times A_{453} - 0.304 \times A_{505} - 1.22 \times A_{645} + 0.216 \times A_{663} \quad (6)$$

2.3. Enzymatic Activity

2.3.1. Extraction

Samples of leaves and ripe fruits of tomatoes were freeze-dried and macerated by using a mortar and pestle; 200 mg of dry tissue and 20 mg of polyvinyl pyrrolidone were added in a 2-mL centrifuge tube; 1.5 mL of phosphate buffer (0.1 M, pH 7–7.2) was added; and the mixture was subjected to sonication for 5 min, and then centrifuged in a Prism C2500 refrigerated microcentrifuge (Labnet International Inc., Edison, NJ, USA) at 14,700× *g* for 10 min at 4 °C. The supernatant was collected and filtered with a 0.45-mm-diameter nylon membrane. Finally, the supernatant was diluted with phosphate buffer (1:20). This dilution was used to analyze the absorbances of reduced glutathione (GSH), glutathione peroxidase (GPX), phenylalanine ammonium lyase (PAL), catalase (CAT), and ascorbate peroxidase (APX) in a GENESYS 10S UV-Vis Spectrum (Thermo Fisher Scientific, Inc., Waltham, MA, USA), as well as the antioxidant capacity of ABTS and DPPH radicals in a BK-EL10C Elisa microplate reader (BIOBASE, Jinan, Shandong, China) at the corresponding wavelengths.

2.3.2. Reduced Glutathione (GSH)

GSH quantification was performed by the spectrophotometric technique [25]. It was made by adding 0.48 mL of the extract, 2.2 mL of Na_2HPO_4 (0.32 M), and 0.32 mL of DTNB (1 mM) to a test tube. The sample was allowed to react for 15 min at room temperature,

and the absorbance was read at a 412 nm wavelength. The results were expressed in units per gram of total protein (U g^{-1} TP), where U is equal to mM of GSH equivalents per mL per minute of dry tissue (mM GSHE mL^{-1} min^{-1} DW).

2.3.3. Glutathione Peroxidase (GPX) (QE 1.11.1.9)

GPX was determined using the Flohé and Günzler [26] method, adapted by Xue et al. [25]. It was performed by adding 0.2 mL of the extract, 0.5 mL of GSH (1 mM), and 0.2 mL of Na_2HPO_4 (0.067 M) to a test tube. The sample was placed in a water bath at 25 °C for 5 min, and 0.2 mL of H_2O_2 was added. The mixture was allowed to react for 10 min, and the reaction was stopped with 1 mL of trichloroacetic acid. The mixture was centrifuged in a C2500 refrigerated microcentrifuge (Labnet Prism®) at 846× *g* for 10 min at 4 °C. Then, 0.48 mL of the obtained mixture, 2.2 mL of Na_2HPO_4 (0.32 M), and 0.32 mL of 5.5 dithionis-2 nitro benzoic acid dye (1 mM) were added to a test tube. The mixture absorbance was read at a 412 nm wavelength. The results were expressed in units per gram of total protein (U g^{-1} TP), where U is equal to mM of GSH equivalents per mL per minute of dry tissue (mM GSHE mL^{-1} min^{-1} DW).

2.3.4. Phenylalanine Ammonium Lyase (PAL) (QE 4.3.1.5)

PAL was determined according to Sykłowska–Baranek et al. [27]. It was performed by adding 0.1 mL of the extract and 0.9 mL of L-phenylalanine (6 mM) to a test tube. The mixture was incubated in a water bath for 30 min at 40 °C, and 0.25 mL of HCl (5 N) was added. The sample was placed in an ice bath, and 5 mL of distilled water was added. The mixture absorbance was read at a 290 nm wavelength. The results were expressed in units per 100 g of total protein (U 100 g^{-1} TP), where U is equal to µmol of trans-cinnamic acid equivalents per mL per minute of dry tissue (µmol TCAE mL^{-1} min^{-1} DW).

2.3.5. Catalase (CAT) (QE 1.11.1.6)

CAT was determined by the spectrophotometric method [28], which is based on the quantification of the H_2O_2 oxidation rate by absorbance difference ($T_0 - T_1$). T_0 was determined by adding 0.1 mL of the extract, 0.4 mL of H_2SO_4 (5%), and 1 mL of H_2O_2 (100 mM) to a test tube. T_1 was computed by adding 0.1 mL of extract and 1 mL of H_2O_2 (100 mM), stirring for 1 min, and adding 0.4 mL of H_2SO_4 (5%). The mixture absorbance was read at a 270 nm wavelength. The results were expressed in units per gram of total protein (U g^{-1} TP), where U is equal to mM of H_2O_2 equivalents spent per mL per minute of dry tissue (mM H_2O_2E mL^{-1} min^{-1} DW).

2.3.6. Ascorbate Peroxidase (APX) (EC 1.11.1.11)

APX quantification was performed according to the Nakano and Asada [29] method, which is based on the quantification of the H_2O_2 oxidation rate by absorbance difference ($T_0 - T_1$). T_0 was determined by adding 0.1 mL of the extract, 0.5 mL of ascorbate (10 mg L^{-1}), 0.4 mL of H_2SO_4 (5%) to stop the reaction, and 1 mL of H_2O_2 (100 mM) to a test tube. T_1 was computed by adding 0.1 mL of extract and 1 mL of H_2O_2 (100 mM) to a test tube, stirring for 1 min, and adding 0.4 mL of H_2SO_4 (5%) to stop the reaction. The mixture absorbance was read at a 266 nm wavelength. The results were expressed in units per gram of total protein (U g^{-1} TP), where U is equal to µmol of ascorbate oxidized equivalents per mL per minute of dry tissue (µmol AOE mL^{-1} min^{-1} DW).

2.4. Antioxidant Capacity

2.4.1. Antioxidant Capacity of Hydrophilic and Lipophilic Compounds by ABTS

Antioxidant activity by the ABTS radical (2,2′-azino-bis-3-ethylbenzothiazolin-6-sulfonic acid) was determined by the spectrophotometric method [30]. It is based on the discoloration of the ABTS radical cation. This radical was obtained from the reaction of ABTS (7 mM) with potassium persulfate (2.45 mM) (1:1) under dark conditions at 25 °C for 16 h.

Subsequently, it was diluted with ethanol (20%) to obtain an absorbance of 0.7 ± 0.01 at a 750 nm wavelength.

The antioxidant capacity of hydrophilic compounds by ABTS was determined by sample extraction performed with phosphate buffer, where 5 µL of extract and 245 µL of the dilution of ABTS radicals (7 mM) were placed in a microplate and allowed to react for 7 min in the dark. The absorbance of the extract was measured at a 750 nm wavelength.

The antioxidant capacity of lipophilic compounds as determined by ABTS was calculated by sample extraction performed with a hexane:acetone solution (3:2). Both the antioxidant capacity results of hydrophilic and lipophilic compounds by ABTS were expressed in µmol of Trolox equivalents per gram of dry tissue (µmol TE g^{-1} DW).

2.4.2. Antioxidant Capacity of Hydrophilic Compounds by DPPH

Antioxidant capacity by DPPH radical (2,2-Diphenyl-1-picrylhydrazyl) was performed according to Brand–Williams et al. [31]. The stock solution was prepared by mixing 2.5 mg of the DPPH radical with 100 mL of methanol. The absorbance of the solution was adjusted to 0.7 ± 0.02 at a 515 nm wavelength.

The antioxidant capacity of hydrophilic compounds by DPPH was determined as follows: 6 µL of the obtained extract was taken with phosphate buffer, and 234 µL of the DPPH radical was added. The decrease in absorbance of the extract after 30 min was measured at a 515 nm wavelength. The antioxidant capacity results of hydrophilic compounds by DPPH were expressed in µmol of Trolox equivalents per gram of dry tissue (µmol TE g^{-1} DW).

2.4.3. Statistical Analyses

The results were analyzed by analysis of variance to determine the variables that presented a significant statistical difference ($p \leq 0.05$) so that the variables with significant effects were submitted to comparison means tests by Tukey ($p \leq 0.05$) using the statistical software InfoStat® 2020e.

3. Results

3.1. Non-Enzymatic Compounds in Tomato Fruits by KIO_3 and Na_2SeO_3 Interactions

The lycopene and β-carotene contents of tomato fruits were significantly modified by KIO_3 and Na_2SeO_3 interactions. The lycopene content increased 110.6% in the 200–2 mg L^{-1} interaction and decreased 77.3% in the 200–3 mg L^{-1} interaction in relation to the control treatment. The β-carotene content increased 157.1% in the 200–1 mg L^{-1} interaction and decreased 90.5% in the 0–0.5 mg L^{-1} interaction in relation to the control treatment (0–0 mg L^{-1} interaction).

Phenol and flavonoid contents in tomato fruits significantly decreased in response to KIO_3 and Na_2SeO_3 interactions. The phenol content increased by 9.7% in the 200–1 mg L^{-1} interaction and decreased by 32.3% in the 150–1 mg L^{-1} interaction in relation to the control treatment. Flavonoid content increased by 13.3% in the 250–1 mg L^{-1} interaction and decreased by 35% in the 200–3 mg L^{-1} interaction in relation to the control treatment.

The vitamin C content in tomato fruits was non-significantly influenced by KIO_3 and Na_2SeO_3 interactions (Table 2).

Table 2. Effect of seed priming based on KIO_3 and Na_2SeO_3 interactions on the non-enzymatic antioxidant compounds in tomato fruits.

Na_2SeO_3	KIO_3	Vitamin C	Phenols	Flavonoids	Lycopene	β-carotene
(mg L^{-1})	(mg L^{-1})	(mg 100 g^{-1} FW)	(mg GAE g^{-1} DW)	(mg QE 100 g^{-1} DW)	(mg 100 g^{-1} DW)	(mg 100 g^{-1} DW)
0	0	18.8 *abcdef*	3.1 *ab*	18.0 *ab*	6.6 *cd*	2.1 *efg*
0	100	17.6 *bcdef*	2.9 *abc*	17.2 *abc*	12.4 *b*	3.8 *abcde*
0	150	21.5 *a*	2.7 *abc*	12.6 *fghi*	4.0 *efg*	1.9 *fgh*
0	200	20.5 *abc*	2.6 *abc*	15.8 *bcdef*	4.3 *efg*	1.6 *fgh*
0	250	18.0 *bcdef*	2.6 *abc*	12.4 *hi*	2.9 *gh*	1.5 *fgh*

Table 2. *Cont.*

Na_2SeO_3 (mg L^{-1})	KIO_3 (mg L^{-1})	Vitamin C (mg 100 g^{-1} FW)	Phenols (mg GAE g^{-1} DW)	Flavonoids (mg QE 100 g^{-1} DW)	Lycopene (mg 100 g^{-1} DW)	β-carotene (mg 100 g^{-1} DW)
0.5	0	19.2 *abcdef*	2.7 *abc*	13.4 *defghi*	4.3 *efg*	0.2 *h*
0.5	100	16.2 *f*	3.0 *abc*	15.4 *bcdefgh*	6.6 *cd*	2.1 *efg*
0.5	150	16.5 *ef*	2.6 *abc*	17.3 *abc*	13.8 *a*	3.9 *abcd*
0.5	200	17.9 *bcdef*	2.8 *abc*	15.7 *bcdefg*	4.9 *ef*	0.8 *gh*
0.5	250	19.5 *abcde*	2.9 *abc*	18.0 *ab*	7.8 *c*	1.7 *fgh*
1	0	19.1 *abcdef*	2.8 *abc*	12.9 *efghi*	3.8 *fg*	2.0 *fg*
1	100	20.6 *ab*	2.7 *abc*	15.1 *bcdefgh*	6.4 *cd*	3.0 *cdef*
1	150	17.1 *def*	2.1 *c*	15.9 *bcde*	6.6 *cd*	4.2 *abc*
1	200	19.8 *abcd*	3.4 *a*	16.8 *bc*	11.6 *b*	5.4 *a*
1	250	19.07 *abcdef*	3.0 *abc*	20.4 *a*	6.9 *c*	4.1 *abcd*
2	0	19.3 *abcde*	2.3 *bc*	17.2 *abc*	3.0 *gh*	2.6 *cdef*
2	100	18.2 *bcdef*	2.7 *abc*	14.8 *cdefghi*	3.2 *gh*	2.7 *cdef*
2	150	18 *bcdef*	3.0 *ab*	17.5 *abc*	11.2 *b*	5.2 *ab*
2	200	16.8 *def*	3.0 *abc*	17.1 *bc*	13.9 *a*	4.9 *ab*
2	250	19.3 *abcdef*	2.9 *abc*	15.8 *bcdef*	6.4 *cd*	3.7 *be*
3	0	19.2 *abcdef*	2.6 *abc*	15.3 *bcdefgh*	2.3 *hi*	2.5 *def*
3	100	19.5 *abcde*	2.9 *abc*	16.2 *bcd*	7.5 *c*	3.8 *abcde*
3	150	17.4 *cdef*	2.8 *abc*	14.9 *bcdefgh*	5.4 *de*	3.8 *abcd*
3	200	18.8 *abcdef*	2.3 *bc*	11.7 *i*	1.5 *i*	1.7 *fgh*
3	250	18.9 *abcdef*	2.7 *abc*	12.5 *ghi*	3.1 *gh*	2.6 *cdef*

Different letters within the columns indicate significant differences between the treatment interactions (Tukey HSD, $p \leq 0.05$). n = 4.

3.2. Non-Enzymatic Compounds in Tomato Fruits by KIO_3 and Na_2SeO_3 Factors

Regarding the potassium iodate factor in the tomato fruits, the vitamin C content significantly decreased by 5.2% with KIO_3 in the 150 mg L^{-1} treatment in relation to the control treatment. Phenol and flavonoid contents were not influenced by KIO_3. Lycopene and β-carotene contents significantly increased with all KIO_3 treatments, where the 150 mg L^{-1} dose allowed reaching increments of 105 and 100% on lycopene and β-carotene contents, respectively, in relation to the control treatment, which contrasts with the results of vitamin C (Figure 1a).

Regarding the sodium selenite factor in the tomato fruits, the vitamin C content significantly increased by 9% with Na_2SeO_3 in the 1 mg L^{-1} treatment in relation to the 0.5 mg L^{-1} treatment. The phenol content was not influenced by Na_2SeO_3. Flavonoid content increased by 8.6% with Na_2SeO_3 in the 2 mg L^{-1} treatment and decreased by 7.2% in the 3 mg L^{-1} doses in relation to the control treatment. The lycopene content increased by 25% with Na_2SeO_3 in the 0.5 and 2 mg L^{-1} treatments and decreased by 35% in the 3 mg L^{-1} treatment, in relation to the control treatment. The β-carotene content increased with Na_2SeO_3 at 1–3 mg L^{-1}, reaching the highest increase by 72.7% in the 2 mg L^{-1} treatment in relation to the control treatment. The Na_2SeO_3 treatment at 2 mg L^{-1} presented the best performance because it resulted in the highest increases in lycopene, β-carotene, and flavonoid contents in tomato fruits in relation to the corresponding control treatment (Figure 1b).

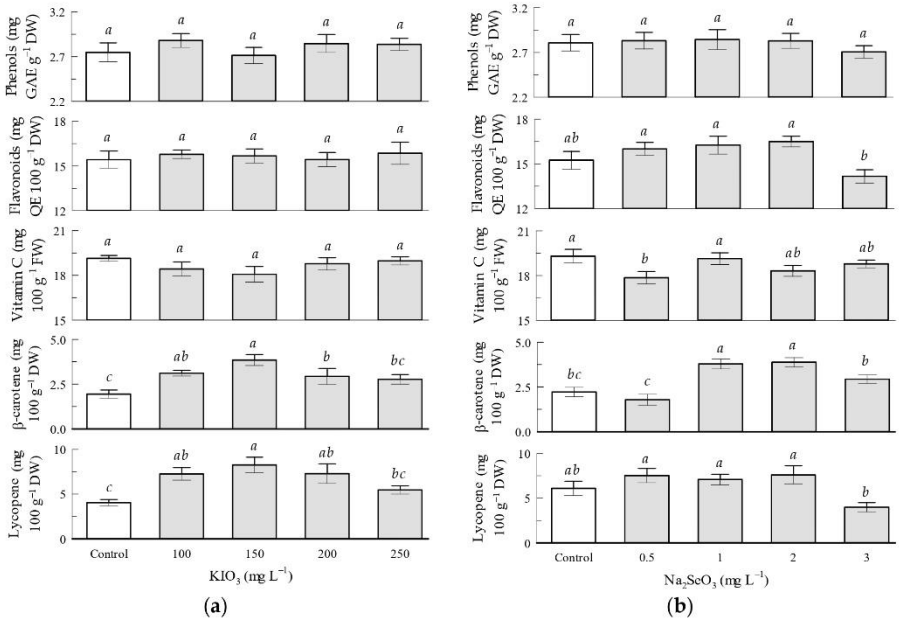

Figure 1. Non-enzymatic antioxidant compounds in tomato fruits: (**a**) Seed priming based on KIO_3; (**b**) Seed priming based on Na_2SeO_3. Different letters indicate significant differences between treatments (Tukey HSD, $p \leq 0.05$). n = 4.

3.3. Non-Enzymatic Compounds in Tomato Leaves by KIO_3 and Na_2SeO_3 Interactions

The phenol content was significantly influenced by KIO_3 and Na_2SeO_3 interactions, that is, increased by 31.6% in the 100–0.5 mg L^{-1} interaction and decreased by 28.4% in the 0–0.5 mg L^{-1} interaction in relation to the control treatment (0–0 mg L^{-1} interaction). The flavonoid content significantly decreased by 21.4% in the 100–3 mg L^{-1} interaction in relation to the control treatment. Chlorophyll and β-carotene were non-significantly influenced by KIO_3 and Na_2SeO_3 interactions in relation to the respective control treatments.

Chlorophyll-*a* and total chlorophyll significantly increased by 3.2% and 2.4%, respectively, in the 100–0 mg L^{-1} interaction in relation to the 0–3 mg L^{-1} interaction, that is, removing the KIO_3 and raising the Na_2SeO_3 doses (Table 3).

Table 3. Effect of seed priming based on KIO_3 and Na_2SeO_3 interactions on the non-enzymatic antioxidant compounds in tomato leaves.

Na_2SeO_3	KIO_3	Phenols	Flavonoids	Chlorophyll *a*	Chlorophyll *b*	Total chl.	β-carotene
(mg L $^{-1}$)	(mg L $^{-1}$)	(mg GAE g $^{-1}$ DW)	(mg QE 100 g $^{-1}$ DW)	(µg g $^{-1}$ FW)	(µg g $^{-1}$ FW)	(µg g $^{-1}$ FW)	(mg 100 g $^{-1}$ DW)
0	0	9.5 *cdef*	60.4 *ab*	93.0 *abc*	81.3 *a*	174.7 *ab*	0.22 *a*
0	100	10.3 *abcde*	58.2 *abc*	94.4 *a*	81.0 *a*	175.8 *a*	0.15 *a*
0	150	10.5 *abcde*	52.8 *abc*	93.1 *abc*	81.3 *a*	174.7 *ab*	0.22 *a*
0	200	11.1 *abcd*	58.1 *abc*	92.8 *abc*	80.8 *a*	174.0 *ab*	0.25 *a*
0	250	8.5 *efg*	48.8 *abc*	91.9 *bc*	80.3 *a*	172.5 *ab*	0.23 *a*
0.5	0	6.8 *g*	51.4 *abc*	92.7 *abc*	80.6 *a*	173.6 *ab*	0.23 *a*
0.5	100	12.5 *a*	48.4 *bc*	94.0 *ab*	81.0 *a*	175.4 *a*	0.24 *a*
0.5	150	9.16 *efg*	55.4 *abc*	92.9 *abc*	81.3 *a*	174.5 *ab*	0.19 *a*
0.5	200	11.13 *bcd*	58.9 *abc*	92.3 *abc*	81.1 *a*	173.7 *ab*	0.24 *a*
0.5	250	9.4 *def*	56.8 *abc*	93.0 *abc*	81.4 *a*	174.7 *ab*	0.28 *a*

Table 3. *Cont.*

Na_2SeO_3 (mg L^{-1})	KIO_3 (mg L^{-1})	Phenols (mg GAE g^{-1} DW)	Flavonoids (mg QE 100 g^{-1} DW)	Chlorophyll *a* (µg g^{-1} FW)	Chlorophyll *b* (µg g^{-1} FW)	Total chl. (µg g^{-1} FW)	β-carotene (mg 100 g^{-1} DW)
1	0	10.7 *abcde*	58.1 *abc*	92.9 *abc*	81.4 *a*	174.6 *ab*	0.23 *a*
1	100	10.1 *abcde*	54.2 *abc*	93.2 *abc*	80.6 *a*	174.1 *ab*	0.24 *a*
1	150	10.7 *abcde*	59.6 *abc*	92.8 *abc*	81.8 *a*	175.0 *ab*	0.21 *a*
1	200	10.5 *abcde*	61.0 *ab*	93.5 *abc*	81.8 *a*	175.7 *a*	0.21 *a*
1	250	11.8 *abc*	59.6 *abc*	92.5 *abc*	82.1 *a*	174.9 *ab*	0.25 *a*
2	0	7.6 *fg*	58.1 *abc*	93.3 *abc*	81.8 *a*	175.4 *a*	0.19 *a*
2	100	9.4 *cdef*	56.3 *abc*	93.6 *abc*	80.1 *a*	174.0 *ab*	0.18 *a*
2	150	11.0 *abcd*	50.4 *abc*	92.9 *abc*	81.0 *a*	174.1 *ab*	0.20 *a*
2	200	9.3 *def*	57.2 *abc*	92.9 *abc*	81.3 *a*	174.6 *ab*	0.21 *a*
2	250	12.1 *ab*	61.4 *a*	92.6 *abc*	81.6 *a*	174.5 *ab*	0.27 *a*
3	0	10.0 *bcdef*	57.1 *abc*	91.5 *c*	79.8 *a*	171.6 *b*	0.24 *a*
3	100	9.9 *bcdef*	47.5 *c*	92.4 *abc*	80.8 *a*	173.5 *ab*	0.26 *a*
3	150	9.3 *def*	60.7 *ab*	93.2 *abc*	82.2 *a*	175.7 *a*	0.20 *a*
3	200	10.2 *abcde*	50.7 *abc*	92.4 *abc*	80.6 *a*	173.3 *ab*	0.23 *a*
3	250	9.0 *defg*	54.7 *abc*	93.5 *abc*	81.9 *a*	175.6 *a*	0.18 *a*

Different letters within the columns indicate significant differences between the treatment interactions (Tukey HSD, $p \leq 0.05$). n = 4.

3.4. Non-Enzymatic Compounds in Tomato Leaves by KIO_3 and Na_2SeO_3 Factors

Regarding the potassium iodate factor in the tomato leaves, the phenol content significantly increased with all KIO_3 treatments, where the 100 and 200 mg L^{-1} treatments reached increments of 16.9% in relation to the control treatment. The chlorophyll-*a* content increased by 0.9% with KIO_3 in the 100 mg L^{-1} treatment in relation to the control treatment. Flavonoid, chlorophyll-*b*, and β-carotene contents were not influenced by KIO_3 (Figure 2a).

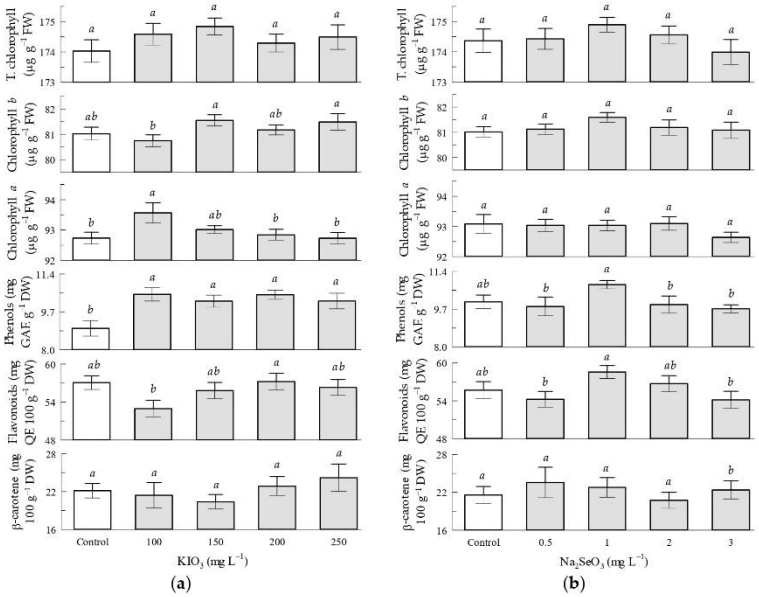

Figure 2. Non-enzymatic antioxidant compounds in tomato leaves: (**a**) Seed priming based on KIO_3; (**b**) Seed priming based on Na_2SeO_3. Different letters indicate significant differences between treatments (Tukey HSD, $p \leq 0.05$). n = 4.

Regarding the sodium selenite factor in the tomato leaves, all the non-enzymatic antioxidant compounds were not significantly influenced by Na_2SeO_3 (Figure 2b).

3.5. Enzymatic Activity in Tomato Fruits by KIO_3 and Na_2SeO_3 Interactions

Regarding the tomato fruits, the (GSH) content and the PAL enzymatic activity were significantly increased by KIO_3 and Na_2SeO_3 interactions: GSH by 35% in the 150–0.5 mg L^{-1} interaction and PAL by 441.7% in the 100–1 mg L^{-1} interaction in relation to the respective control treatments (0–0 mg L^{-1} interaction).

On the other hand, the enzymatic activities of GPX, CAT, and APX were not significantly influenced by KIO_3 and Na_2SeO_3 interactions in relation to the respective control treatments.

Lower and higher changes in GPX values were −30.6 and 238.9% in the 100–2 and 0–3 mg L^{-1} interactions, respectively, in relation to the corresponding control treatments. Lower and higher changes in CAT values were −14.8 and 70.4% in the 0–3 and 100–3 mg L^{-1} interactions, respectively, in relation to the corresponding control treatments. Lower and higher changes in APX values were −46.4 and 21.4% in the 150–1 and 100–2 mg L^{-1} interactions, respectively, in relation to the corresponding control treatments (Table 4).

Table 4. Effect of seed priming based on KIO_3 and Na_2SeO_3 interactions on the enzymatic activity in tomato fruits.

Na_2SeO_3	KIO_3	GSH	GPX	PAL	CAT	APX
(mg L^{-1})	(mg L^{-1})	(U g^{-1} TP)	(U g^{-1} TP)	(U 100 g^{-1} TP)	(U g^{-1} TP)	(U g^{-1} TP)
0	0	0.20 *bc*	0.36 *ab*	1.2 *b*	2.7 *ab*	2.8 *ab*
0	100	0.22 *abc*	0.59 *ab*	4.1 *ab*	2.9 *ab*	2.3 *ab*
0	150	0.21 *abc*	0.54 *ab*	4.4 *ab*	4.0 *ab*	2.7 *ab*
0	200	0.20 *abc*	0.77 *ab*	4.7 *ab*	3.1 *ab*	2.9 *ab*
0	250	0.20 *abc*	0.57 *ab*	3.7 *ab*	3.2 *ab*	2.7 *ab*
0.5	0	0.20 *bc*	0.47 *ab*	3.0 *ab*	2.6 *ab*	3.0 *ab*
0.5	100	0.20 *abc*	0.48 *ab*	3.6 *ab*	2.6 *ab*	1.9 *ab*
0.5	150	0.27 *a*	0.71 *ab*	3.8 *ab*	2.9 *ab*	1.6 *ab*
0.5	200	0.25 *abc*	0.72 *ab*	2.3 *ab*	3.0 *ab*	2.2 *ab*
0.5	250	0.21 *abc*	0.46 *ab*	1.7 *b*	2.5 *ab*	2.3 *ab*
1	0	0.20 *abc*	0.73 *ab*	3.0 *ab*	3.0 *ab*	2.0 *ab*
1	100	0.25 *abc*	0.43 *ab*	2.3 *ab*	2.8 *ab*	2.4 *ab*
1	150	0.22 *abc*	0.72 *ab*	4.1 *ab*	3.0 *ab*	1.5 *b*
1	200	0.26 *a*	0.70 *ab*	6.5 *a*	3.4 *ab*	2.4 *ab*
1	250	0.25 *abc*	0.60 *ab*	3.2 *ab*	2.4 *ab*	2.3 *ab*
2	0	0.21 *abc*	0.68 *ab*	2.4 *ab*	2.7 *ab*	2.8 *ab*
2	100	0.19 *c*	0.25 *b*	5.0 *ab*	3.3 *ab*	3.4 *a*
2	150	0.24 *abc*	0.47 *ab*	5.4 *ab*	2.5 *ab*	2.4 *ab*
2	200	0.26 *ab*	0.61 *ab*	4.4 *ab*	2.8 *ab*	2.3 *ab*
2	250	0.25 *abc*	0.38 *ab*	4.4 *ab*	2.9 *ab*	2.9 *ab*
3	0	0.24 *abc*	1.22 *a*	2.8 *ab*	2.3 *b*	2.2 *ab*
3	100	0.26 *abc*	1.22 *ab*	3.3 *ab*	4.6 *a*	1.9 *ab*
3	150	0.23 *abc*	0.57 *ab*	3.9 *ab*	2.5 *ab*	2.2 *ab*
3	200	0.22 *abc*	0.58 *ab*	2.5 *ab*	2.6 *ab*	2.7 *ab*
3	250	0.23 *abc*	1.04 *ab*	3.0 *ab*	2.5 *ab*	2.2 *ab*

Different letters within the columns indicate significant differences between the treatment interactions (Tukey HSD, $p \leq 0.05$). n = 4.

3.6. Enzymatic Activity in Tomato Fruits by KIO_3 and Na_2SeO_3 Factors

Regarding the potassium iodate factor in the tomato fruits, the KIO_3 treatments at 150 and 200 mg L^{-1} significantly increased the GSH content by 9.5 and 14.3%, and the PAL enzymatic activity by 72 and 64%, respectively, in relation to the corresponding control

treatments. GPX, CAT, and APX enzymatic activities were not significantly influenced by KIO_3 (Figure 3a).

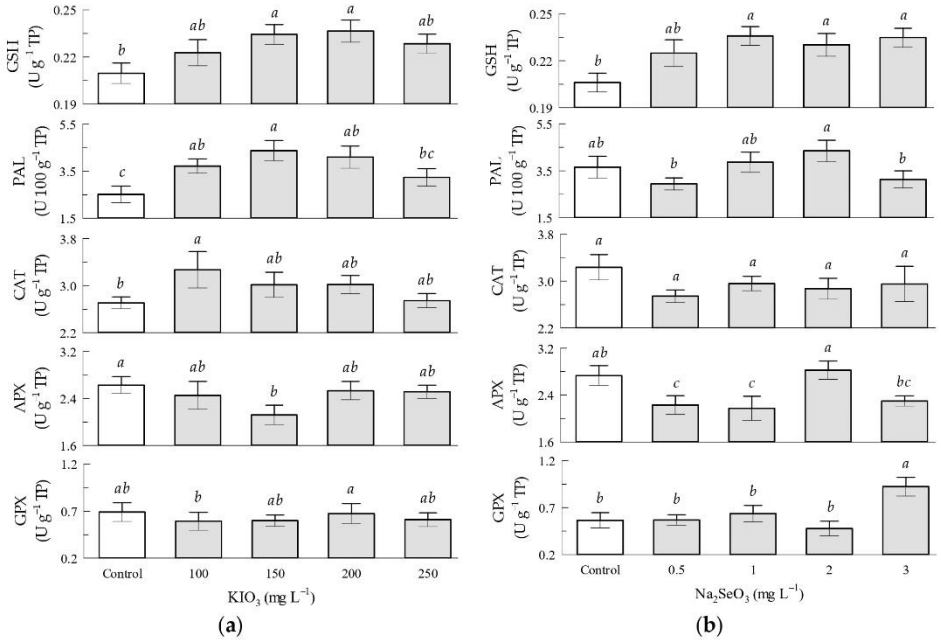

Figure 3. Enzymatic antioxidant compounds in tomato fruits: (**a**) Seed priming based on KIO_3; (**b**) Seed priming based on Na_2SeO_3. Different letters indicate significant differences between treatments (Tukey HSD, $p \leq 0.05$). n = 4.

Regarding the sodium selenite factor in the tomato fruits, the GSH content was significantly increased by Na_2SeO_3 by 14.3% and 9.5% in the 1 and 2–3 mg L^{-1} treatments, respectively, in relation to the corresponding control treatments. GPX enzymatic activity significantly increased by 64.3% by Na_2SeO_3 in the 3 mg L^{-1} treatment in relation to the control treatment (Figure S2). PAL, CAT, and APX enzymatic activities were not significantly influenced by Na_2SeO_3 in relation to the respective control treatments. APX enzymatic activity significantly increased by 33.3% by Na_2SeO_3 in the 2 mg L^{-1} treatment in relation to the 1 mg L^{-1} treatment (Figure 3b).

3.7. Enzymatic Activity in Tomato Leaves by KIO_3 and Na_2SeO_3 Interactions

GSH content and enzymatic activity of GPX in tomato leaves were significantly increased by KIO_3 and Na_2SeO_3 interactions; GSH by 27.3% in the 200–0 mg L^{-1} interaction and GPX by 80% in the 150–0.5 mg L^{-1} interaction, in relation to the respective control treatments (0–0 mg L^{-1} interaction). The enzymatic activities of PAL, CAT, and APX were not significantly modified by KIO_3 and Na_2SeO_3 interactions.

Higher enzymatic activities occurred for PAL in the 0–0.5 mg L^{-1} interaction, for CAT in the 250–0.5 mg L^{-1} interaction, and for APX in the 0–2 mg L^{-1} interaction (Table 5).

Table 5. Effect of seed priming based on KIO_3 and Na_2SeO_3 interactions on the enzymatic activity in tomato leaves.

Na_2SeO_3 (mg L^{-1})	KIO_3 (mg L^{-1})	GSH (U g^{-1} TP)	GPX (U g^{-1} TP)	PAL (U 100 g^{-1} TP)	CAT (U g^{-1} TP)	APX (U g^{-1} TP)
0	0	1.1 *cdefg*	1.0 *bcd*	13.9 *abc*	3.5 *abc*	4.6 *ab*
0	100	1.1 *bcdefg*	0.9 *cd*	12.4 *abc*	2.5 *abc*	2.1 *ab*
0	150	1.1 *bcdefg*	1.0 *cd*	11.7 *abc*	1.8 *bc*	2.4 *ab*
0	200	1.4 *a*	0.9 *cd*	13.8 *abc*	2.2 *abc*	1.5 *ab*
0	250	1.2 *abcd*	0.7 *d*	18.6 *ab*	4.1 *abc*	2.1 *ab*
0.5	0	1.0 *defg*	1.4 *abc*	19.9 *a*	2.1 *abc*	4.2 *ab*
0.5	100	1.2 *abcd*	1.1 *abcd*	17.0 *abc*	2.5 *abc*	2.1 *ab*
0.5	150	1.0 *defg*	1.8 *a*	18.7 *ab*	4.4 *abc*	4.6 *ab*
0.5	200	1.0 *cdefg*	1.7 *ab*	9.5 *c*	2.2 *abc*	3.2 *ab*
0.5	250	0.9 *g*	1.2 *abcd*	13.7 *abc*	6.3 *a*	4.2 *ab*
1	0	1.0 *cdefg*	1.0 *cd*	13.9 *abc*	3.9 *abc*	2.7 *ab*
1	100	1.2 *abcdef*	1.0 *cd*	9.5 *c*	3.5 *abc*	1.2 *ab*
1	150	1.1 *abcdefg*	1.1 *bcd*	8.7 *c*	1.8 *bc*	3.1 *ab*
1	200	1.3 *abc*	1.1 *bcd*	8.7 *c*	2.4 *abc*	3.1 *ab*
1	250	1.1 *abcdefg*	1.2 *abcd*	11.6 *abc*	4.9 *abc*	4.2 *ab*
2	0	0.9 *fg*	1.2 *abcd*	19.1 *ab*	6.1 *ab*	4.9 *a*
2	100	1.0 *defg*	0.6 *d*	10.5 *bc*	2.8 *abc*	1.6 *ab*
2	150	0.9 *efg*	0.7 *d*	10.9 *abc*	0.9 *c*	2.5 *ab*
2	200	1.1 *abcdefg*	1.3 *abcd*	12.5 *abc*	2.9 *bc*	2.8 *ab*
2	250	1.3 *ab*	1.0 *cd*	13.7 *abc*	0.7 *c*	2.8 *ab*
3	0	1.1 *bcdefg*	0.9 *cd*	12.8 *abc*	1.8 *bc*	2.2 *ab*
3	100	1.1 *abcdefg*	0.9 *cd*	11.1 *abc*	0.6 *c*	2.1 *ab*
3	150	1.2 *abcde*	0.9 *cd*	12.5 *abc*	1.7 *c*	1.2 *ab*
3	200	1.1 *abcdefg*	1.0 *cd*	12.3 *abc*	2.3 *abc*	0.8 *b*
3	250	1.1 *abcdefg*	1.1 *abcd*	12.1 *abc*	2.6 *abc*	1.4 *ab*

Different letters within the columns indicate significant differences between the treatment interactions (Tukey HSD, $p \leq 0.05$). n = 4.

3.8. Enzymatic Activity in Tomato Leaves by KIO_3 and Na_2SeO_3 Factors

Regarding the potassium iodate factor in the tomato leaves, by increasing the KIO_3 concentration from 100 to 200 mg L^{-1}, the GSH content significantly increased from 10 to 20%, the enzymatic activity of PAL decreased from 23.9 to 28.9%, and the enzymatic activity of APX decreased from 51.4 to 37.8%. The enzymatic activities of CAT and APX were not significantly influenced by KIO_3 (Figure 4a).

Regarding the sodium selenite factor in the tomato leaves, the GSH content significantly decreased by Na_2SeO_3 by 16.7 and 8.3% in the 0.5 and 2 mg L^{-1} treatments, respectively, in relation to the control treatment. The enzymatic activity of GPX significantly increased by 55.6% with Na_2SeO_3 in the 0.5 mg L^{-1} treatment in relation to the control treatment. The enzymatic activities of PAL, CAT, and APX were not significantly influenced by Na_2SeO_3 (Figure 4b).

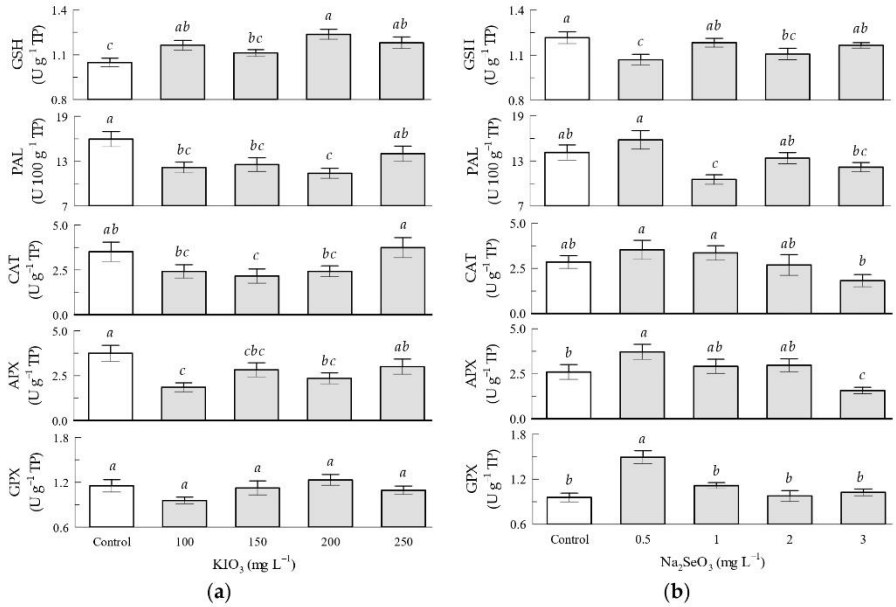

Figure 4. Enzymatic antioxidant compounds in tomato leaves: (**a**) Seed priming based on KIO_3; (**b**) Seed priming based on Na_2SeO_3. Different letters indicate significant differences between treatments (Tukey HSD, $p \leq 0.05$). n = 4.

3.9. Antioxidant Capacity in Tomato Fruits and Leaves by KIO_3 and Na_2SeO_3 Interactions

Regarding the tomato fruits, the antioxidant capacity of hydrophilic compounds by the ABTS radical significantly decreased by 64.1% in the 200–2 mg L^{-1} (KIO_3-Na_2SeO_3) interaction in relation to the control treatment (0–0 mg L^{-1} interaction). The antioxidant capacity of lipophilic compounds by ABTS and hydrophilic compounds by DPPH radicals was not significantly influenced by KIO_3 and Na_2SeO_3 interactions. Higher values of antioxidant capacity of hydrophilic compounds by DPPH occurred in the 0–0.5 mg L^{-1} interaction (Table 6).

Table 6. Effect of seed priming based on KIO_3 and Na_2SeO_3 interactions on the antioxidant capacity (µmol TE g^{-1} DW) in tomato fruits and leaves.

Na_2SeO_3 (mg L^{-1})	KIO_3 (mg L^{-1})	Fruits ABTS-H	Fruits ABTS-L	Fruits DPPH-H	Leaves ABTS-H	Leaves ABTS-L	Leaves DPPH-H
0	0	28.7 *a*	6.6 *a*	43.7 *abc*	47.8 *ab*	20.1 *abc*	21.5 *e*
0	100	27.5 *ab*	8.4 *a*	34.1 *abc*	64.7 *ab*	14.6 *bc*	22.3 *de*
0	150	27.0 *ab*	4.0 *a*	41.0 *abc*	44.2 *ab*	17.7 *abc*	34.4 *bcde*
0	200	25.3 *ab*	3.2 *a*	42.0 *abc*	61.6 *ab*	15.8 *abc*	26.0 *cde*
0	250	27.1 *ab*	7.1 *a*	44.9 *abc*	55.3 *ab*	19.0 *abc*	36.0 *abcde*
0.5	0	20.3 *abc*	8.8 *a*	50.2 *a*	47.0 *ab*	13.1 *bc*	28.5 *cde*
0.5	100	19.3 *abc*	8.4 *a*	36.6 *abc*	56.3 *ab*	10.9 *c*	36.1 *abcde*
0.5	150	16.8 *abc*	4.7 *a*	41.3 *abc*	59.4 *ab*	10.3 *c*	40.0 *abcde*
0.5	200	26.4 *ab*	1.4 *a*	41.9 *abc*	45.7 *ab*	26.2 *a*	28.9 *cde*
0.5	250	27.4 *ab*	3.6 *a*	36.5 *abc*	42.7 *ab*	13.6 *bc*	22.3 *de*

Table 6. *Cont.*

Na_2SeO_3 (mg L^{-1})	KIO_3 (mg L^{-1})	Fruits ABTS-H	Fruits ABTS-L	Fruits DPPH-H	Leaves ABTS-H	Leaves ABTS-L	Leaves DPPH-H
1	0	17.3 *abc*	1.8 *a*	26.2 *abc*	52.1 *ab*	18.1 *abc*	28.0 *cde*
1	100	16.3 *abc*	2.3 *a*	35.6 *abc*	44.4 *ab*	12.7 *bc*	27.0 *cde*
1	150	27.8 *ab*	4.3 *a*	46.9 *ab*	55.3 *ab*	19.9 *abc*	48.3 *abcd*
1	200	18.1 *abc*	4.3 *a*	32.2 *abc*	44.5 *ab*	14.0 *bc*	49.7 *abc*
1	250	15.3 *bc*	2.6 *a*	32.1 *abc*	46.2 *ab*	14.0 *bc*	36.2 *abcde*
2	0	17.0 *abc*	1.7 *a*	29.4 *abc*	40.4 *b*	18.9 *abc*	36.1 *abcde*
2	100	17.2 *abc*	4.2 *a*	23.1 *b*	44.8 *ab*	19.7 *abc*	61.5 *a*
2	150	12.1 *c*	6.6 *a*	20.8 *c*	44.9 *ab*	22.5 *ab*	29.0 *cde*
2	200	10.3 *c*	3.4 *a*	28.3 *abc*	50.0 *ab*	18.9 *abc*	61.7 *a*
2	250	15.6 *abc*	2.7 *a*	26.5 *abc*	50.0 *ab*	16.4 *abc*	52.5 *abc*
3	0	18.2 *abc*	9.7 *a*	28.3 *abc*	53.0 *ab*	22.3 *ab*	56.1 *ab*
3	100	22.3 *abc*	9.6 *a*	30.7 *abc*	48.0 *ab*	19.3 *abc*	49.1 *abc*
3	150	11.8 *c*	2.3 *a*	29.4 *abc*	67.0 *a*	18.2 *abc*	42.7 *abcde*
3	200	14.9 *bc*	5.3 *a*	25.5 *abc*	54.4 *ab*	13.4 *bc*	21.6 *e*
3	250	23.2 *abc*	2.4 *a*	30.9 *abc*	57.5 *ab*	20.0 *abc*	46.9 *abcde*

-H hydrophilic, -L lipophilic. Different letters within the columns indicate significant differences between the treatment interactions (Tukey HSD, $p \leq 0.05$). n = 4.

Regarding the tomato leaves, the antioxidant capacity of hydrophilic compounds by DPPH radical significantly increased by 187% in the 200–2 mg L^{-1} interaction, in relation to the control treatment. The antioxidant capacity of hydrophilic and lipophilic compounds by the ABTS radicals was not significantly influenced by KIO_3 and Na_2SeO_3 interactions. Higher values of antioxidant capacity of hydrophilic compounds by ABTS occurred in the 150–3 mg L^{-1} interaction and for lipophilic compounds by ABTS in the 200–0.5 mg L^{-1} interaction (Table 6).

3.10. Antioxidant Capacity in Tomato Fruits and Leaves by KIO_3 and Na_2SeO_3 Factors

Regarding the potassium iodate factor, the antioxidant capacity of hydrophilic compounds by ABTS and by DPPH and of lipophilic compounds by ABTS was not significantly influenced by KIO_3 in tomato fruits (Figure 5a) and leaves (Figure 6a). The antioxidant capacity of lipophilic compounds by ABTS in tomato fruits increased 88.6% with KIO_3 in the 100 mg L^{-1} treatment in relation to the 200 mg L^{-1} treatment (Figure 5a).

Regarding the sodium selenite factor in the tomato fruits, the antioxidant capacity of hydrophilic compounds by ABTS and by DPPH was negatively affected by Na_2SeO_3, where the 2 mg L^{-1} treatment presented higher inhibition of these parameters by 46.9 and 37.7%, respectively (Figure 5b).

Regarding the sodium selenite factor in the tomato leaves, the antioxidant capacity of hydrophilic compounds by DPPH significantly increased by Na_2SeO_3 35.4%, 71.8%, and 54.6% in the 1, 2, and 3 mg L^{-1} treatments, respectively. The antioxidant capacity of hydrophilic compounds by ABTS significantly decreased by 15.9% by Na_2SeO_3 in the 2 mg L^{-1} treatment in relation to the control treatment. The antioxidant capacity of lipophilic compounds by ABTS was not significantly influenced by Na_2SeO_3 in tomato fruits and leaves (Figure 6b).

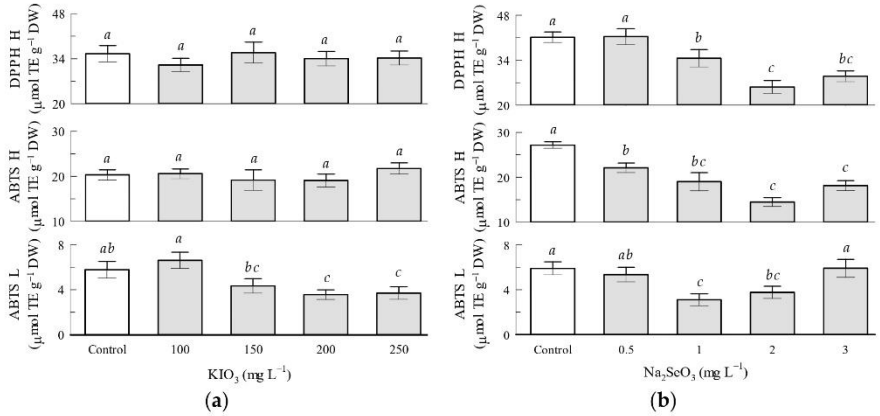

Figure 5. Antioxidant capacity of tomato fruits: (**a**) Seed priming based on KIO_3; (**b**) Seed priming based on Na_2SeO_3. Different letters indicate significant differences between treatments (Tukey HSD, $p \leq 0.05$). n = 4.

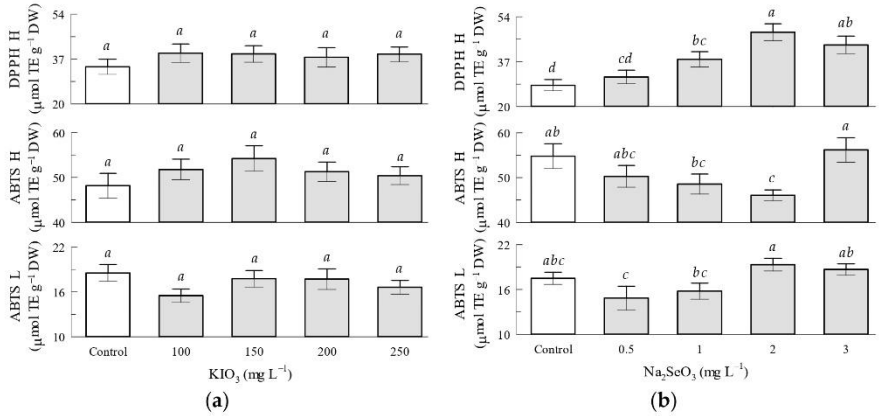

Figure 6. Antioxidant capacity of tomato leaves: (**a**) Seed priming based on KIO_3; (**b**) Seed priming based on Na_2SeO_3. Different letters indicate significant differences between treatments (Tukey HSD, $p \leq 0.05$). n = 4.

4. Discussion

Implementation of techniques such as seed imbibition is an effective method to improve the response of plants to biotic and abiotic stress conditions (Table S1) through the alteration of antioxidant metabolism [10]. Important findings of seed imbibition are reported, such as the antioxidant response of broccoli influenced by selenium [32], the salt stress tolerance of strawberries influenced by iodine species [33], and the functional effects of selenium in crucifers [34].

Plants can absorb different chemical elements from the soil or the nutrient solution, whether these elements are beneficial or toxic [35]. Selenium can be absorbed through the roots in the form of selenate (SeO_4^{2-}), selenite (SeO_3^{2-}), and organic Se compounds such as selenocysteine (SeCys) and selenomethionine (SeMet) (Table S2), but selenides or

elemental Se cannot be absorbed [36]. The use of selenium in plants has been reported to have positive effects on glutathione content, because selenium increases sulfur (S) receptors and consequently increases the absorption of both elements, favoring the synthesis of secondary metabolites [37].

Plant cells produce free oxygen and its derivatives, such as reactive oxygen species (ROS), which are used as signaling molecules in plants in signal translation in response to environmental conditions; this triggers antioxidant defense mechanisms. In this context, it has been shown that the optimal addition of iodine (Figure S3) and selenium presents an alteration in the ROS production system [38,39], where the enzymatic defense systems, such as catalase, peroxidase, superoxide dismutase, glutathione peroxidase, and ascorbate peroxidase, and non-enzymatic antioxidants, such as glutathione, ascorbate, tocopherols, and phenolic compounds, are activated (Figure S4) to reduce the excessive ROS production [40]. For its part, the SOD enzyme dismutases the O_2^- into hydrogen peroxide H_2O_2 and molecular oxygen O_2, and later the catalase (CAT) degrades the H_2O_2 into oxygen and water, while the ascorbate peroxidase uses the ascorbic acid as a donor to stimulate the degradation of H_2O_2, and the reduced glutathione is responsible for the production of ascorbic acid [41]. Glutathione reductase catalyzes the regeneration of reduced glutathione (GSH) from glutathione disulfide (GSSG) with NADPH as the reducing agent. GSH eliminates H_2O_2 by non-enzymatic reaction with O_2^- and OH^-, likewise, GSH has the ability to replenish ascorbic acid through the ascorbate-glutathione cycle, which is of great importance for the antioxidant system [42].

4.1. Non-Enzymatic Compounds

In this research, the use of iodine and selenium concentrations applied to tomato crops by seed priming presented increases in the content of flavonoids, lycopene, and carotene in tomato fruits (Figure S2). These results agree with those reported by Gaucin–Delgado et al. [43], who applied 2 mg L^{-1} Na_2SeO_4 in the nutrient solution, presenting an increase in the content of phenols in the tomato crop. Likewise, Cunha et al. [44] and Ishtiaq et al. [45] indicated that the use of selenium presents an increase in chlorophyll, carotenes, and phenolic compounds when using concentrations of 7.5 and 15 µg kg^{-1}, while Sabatino et al. [46] indicated that the use of concentrations of 2 and 4 µmol of SeO_2 presented a higher content in carotenes in relation to the control. Phenol and vitamin C contents in tomato fruits did not present significant effects between treatments, which are similar to those reported by Smoleń et al. [47], who indicated that the use of KIO_3 in conjunction with Na_2SeO_3 at concentrations of 30 and 8.5 µg dm^{-3}, respectively, did not present a significant effect in relation to the control.

The use of KIO_3 influenced an increase in the phenol and chlorophyll-*a* contents; however, the Na_2SeO_3 treatments did not significantly modify these parameters in the leaves in relation to the control. Similar results were reported by Jerse et al. [48], who mentioned that the use of Na_2SeO_3 at 10 mg L^{-1} in conjunction with KIO_3 at concentrations of 1000 mg L^{-1} did not present an effect on photosynthetic compounds, likewise indicating that the use of iodine concentrations and selenium separately reduced the dry matter content. However, when both elements interacted, there was a higher biomass content, which is similar to that reported by Smoleń et al. [49], who found that the separate use of selenium and vanadium promotes iodine uptake in plants.

Wang et al. [50] indicated that imbibition treatments present an increase in the content of polyphenols in the rye, which is attributed to the synthesis or activation of a variety of hydrolytic enzymes, causing different alterations in the structure or the synthesis of new compounds with high bioactivity and nutritional value. On the other hand, Vicas et al. [51] indicated that the use of selenium nanoparticles did not affect the phenol content of the broccoli crop. Likewise, Islam et al. [52] indicated that at a higher concentration of Na_2SeO_3, the phenol content begins to decrease. In the same way, Shohag et al. [53] indicated that the imbibed soybean and bean seeds presented a decrease in the phenol content in seeds and sprouts. This decrease in the phenol content is attributed to the imbibition time (Figure S1)

since it is considered that the longer the imbibition time, the greater the water absorption, which presents a dilution effect.

Jerše et al. [48] indicated that the use of iodine and selenium in the imbibition of seeds is a viable method because the enrichment of the pea shoots was achieved with the use of both elements; however, the uptake depends on the shape and/or combinations of the elements. The same effect was reported by Deng et al. [54] and Radawiec et al. [55], who indicated that in osmoconditioning treatments with iron, copper, manganese, zinc, selenium, and iodine in soybean and wheat seeds, they present an increase in the speed of germination and accumulation of these compounds in the shoots, for which they define seed imbibition treatments as a simple and highly efficient technique to increase the content of organic mineral elements in sprouts.

4.2. Enzymatic Activity

Regarding the enzymatic activity, the use of KIO_3 presented an improvement in the GSH content and a greater enzymatic activity in PAL (Figure S3); similar results are reported by Blasco et al. [56], who indicated that the use of iodide (I^-) and iodate (IO_3^-) in lettuce plants presents an increase in antioxidant enzymes. On the other hand, Na_2SeO_3 presented a higher GSH and GPX content (Figure S2); similar results were reported by Zhu et al. [13] and Rady et al. [57], where the use of selenium concentrations favors the increase in the GSH and GPX contents in the tomato crop. The increase in the GHS content is beneficial since high concentrations are needed to overcome oxidative stress in chloroplasts and other organelles [58].

Cao et al. [59], Diao et al. [60], and Kumar et al. [10] indicated that the use of Na_2SeO_3 increases the enzymatic activity compared to the control, presenting an increase in GPX, CAT, and APX, while Nawaz et al. [61] indicated that the enzymatic activity of CAT and APX is increased in seed imbibition treatments with Se. Hu et al. [62] indicated that the use of selenium in the seed imbibition solution presents an increase in the α-amylase content, an increase in the sugar content, and an increase in the enzymatic activity of superoxide dismutase (SOD), glutathione peroxidase (GPX), and catalase (CAT), in addition to presenting a higher total chlorophyll content and Se content in the seedlings; however, this depends on the imbibition time of the seeds. Nawaz et al. [61] indicated that using selenium and exogenous zinc in seed's imbibition increases germination index, vigor, and enzymatic antioxidants such as catalase, guaiacol peroxidase, superoxide dismutase, and ascorbate peroxidase.

4.3. Antioxidant Capacity

Regarding the antioxidant capacity, there was a positive response when using Na_2SeO_3 in the leaves by DPPH of hydrophilic compounds, while Fuentes et al. [63], Medrano Macías et al. [33], and Sarrou et al. [64] indicated that the use of KIO_3 does not affect the antioxidant capacity in strawberry and tomato crops.

5. Conclusions

The application of potassium iodate and sodium selenite in tomato crops by seed imbibition treatments influenced significant changes in non-enzymatic antioxidant compounds, such as phenols, lycopene, β-carotene, and reduced glutathione, as well as on enzymes, that is, phenylalanine ammonium lyase, catalase, and ascorbate peroxidase, both in tomato leaves and fruits; however, the same treatments influenced not significant changes in the antioxidant capacity. Seed priming based on trace elements is a useful and simple technique to perform in agricultural and horticultural production systems. Although this method does not present inconvenience due to the low concentrations of trace elements required, it is necessary to carry out more studies to establish the optimal concentrations according to the crop and the form of application, which allow for improvement of the desired indicators, such as the antioxidant compound pool of the edible organs of the plants, understand the balance and pathway of trace elements in the plant, and the benefits of biofortification of the fruits.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/antiox12061265/s1. Table S1: List of some patented seed priming treatments commercially available; Table S2: Summary of selenoprotein functions; Figure S1: Ranges of selenium application in several crops, applications form to achieve benefits such as biofortification and stimulation; Figure S2: Biochemical and ionomic effects of selenium and nanoselenium application in plants; Figure S3: Uptake, transport and metabolism of iodine in plants; Figure S4: Iodine as a modulator of antioxidants.

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SEGUNDO ARTICULO

Effect of root imbibition with Selenium and Iodine on antioxidant compounds in tomato (*Solanum lycopersicum* L.) crop.

Effect of root imbibition with Selenium and Iodine on antioxidant compounds in tomato (*Solanum lycopersicum* L.) crop

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Abstract

The use of trace elements such as iodine and selenium in agriculture is gaining great importance due to the benefits in plants before different types of biotic or abiotic stress. This research aimed to evaluate the seedling root priming with Na_2SeO_3 (0, 0.5, 1, 2, 3 mg L^{-1}) and KIO_3 (0, 100, 150, 200, 250 mg L^{-1}) on the antioxidant compounds of tomato (*Solanum lycopersicum* L.) fruits and leaves. The crop was established under greenhouse conditions in 10-L polyethylene containers containing peat moss and perlite 1:1 (v/v), in a randomized complete block experimental design with a 5^2 factorial arrangement. In the fruits, the Na_2SeO_3 influenced the GHS, flavonoids, lycopene and β-carotene contents, while the KIO_3 influenced the GHS, vitamin C and lycopene contents. The KIO_3-Na_2SeO_3 interactions affected the GSH, phenols, flavonoids, lycopene and β-carotene contents in fruits. In the leaves the GHS content increased with the Na_2SeO_3, while the GSH, flavonoids, and chlorophyll contents increased with the KIO_3 factor and KIO_3-Na_2SeO_3 interactions. The evaluated enzymes in fruits and leaves decreased with the both the KIO_3 and Na_2SeO_3 concentrations. The Na_2SeO_3 influenced the hydrophilic compounds by ABTS and DPPH, while the KIO_3 influenced the hydrophilic compounds by ABTS. In the leaves, the KIO_3 influenced the lipophilic compounds by ABTS. The KIO_3-Na_2SeO_3 interactions influenced the hydrophilic compounds by ABTS in both the fruits and leaves. Seedling root imbibition in KIO_3 and Na_2SeO_3 is a method that implemented in the tomato crop presents interesting aspects in the increase of the antioxidant capacity and the non-enzymatic compounds, such as vitamin C, phenols, flavonoids and GSH contents. However, this method presented an inhibition in the antioxidant enzymes.

Keywords: Antioxidant, KIO_3, Na_2SeO_3, ROS, secondary metabolites.

Introduction

The use of trace elements such as iodine (I) and selenium (Se) in agriculture is a practice that is gaining great importance and relevance worldwide, because I and Se can promote growth and the potential for tolerance to plant stress when applied in low concentrations (Hasanuzzaman *et al*., 2010). Selenium (Se) is classified as an inorganic plant biostimulant, it has shown an improvement in the absorption of nutrients, increases the tolerance of plants to stress and improves the quality of crop

yields (de Mello Prado, 2021; Dima *et al*., 2020; Hasanuzzaman *et al*., 2020). I and Se in low concentrations can function as signalers to improve the plant's defense system, which is reflected in the increase in the content of secondary metabolites; however, in high concentrations it can cause oxidative damage to tissues (Abedi *et al*., 2021; Mittler, 2017).

Plants have the ability to absorb chemical elements from the soil and from the nutrient solution, whether these are nutrients or non-nutrients, as well as beneficial or toxic (Kathpalia and Bhatla, 2018). Se is absorbed by plant roots in the rhizosphere solution in its organic form as selenocysteine (SeCys) and selenomethionine (SeMet), and its inorganic form as selenate (SeO_4^{2-}) and selenite (SeO_3^{2-}), but selenides or elemental Se cannot be absorbed by plant roots (White, 2018).

Plants are capable of absorbing selenate and selenite ions in the root; however, none of the ions are absorbed through a specific Se transporter. Selenate is absorbed through the H+/sulfate importer. Sulfate transporters SULTR1;1 and SULTR1;2 are high-affinity transporters that absorb sulfate in the root, and have been shown to be capable of transporting selenate, while the selenite is taken up by inorganic phosphate (Pi) transporters and aquaporins (Schiavon and Pilon-Smits, 2017; Trippe and Pilon-Smits, 2021; White, 2018).

Iodine can be absorbed from the soil through the plant roots as organic iodine ions, iodate (IO_3) and iodide (I), and from the atmosphere in gaseous form by the plant leaves as molecular iodine (I_2) and methyl iodide (CH_3I) (Medrano-Macías *et al*., 2016).

Iodine and selenium play important roles with benefit in crop plants particularly under stress conditions, presenting positive effects in reducing the H_2O_2 and O_2^- contents (Zhu *et al*., 2017), that is, have an effect on the activation of the defense system to control the production and accumulation of reactive oxygen species (ROS). In this context, the plant cell system increases the levels of non-enzymatic antioxidant metabolites, including glutathione, ascorbate, tocopherol, phenolic compounds, anthocyanins (Halka *et al*., 2019; Huang *et al*., 2019), and a wide network of enzymatic antioxidants, such as superoxide dismutases (SOD), catalases (CAT), ascorbate peroxidases (APX) and glutathione reductases (GR), among others (Mittler *et al*., 2004; Revelou *et al*., 2022).

Tomato (*Solanum lycopersicum* L.) is a horticultural crop of worldwide importance due to its wide consumption as a processed byproduct and fresh presentation. This research aimed to evaluate the effect of seed priming based on I and Se on the antioxidant compounds of tomato fruits and leaves.

Materials and Methods

Crop establishment

Tomato crop was established in a tunnel-type greenhouse with plastic cover and natural ventilation in the Horticulture Department at the Universidad Autónoma Agraria Antonio Narro, in Saltillo, Mexico (25° 21’ NL, 101° 01’ WL, altitude 1743 m). The average conditions in the greenhouse in the crop cycle were: temperature 21 °C, relative humidity 51%, solar radiation 735 W m^{-2}, photosynthetically active radiation 568 µmol m^{-2} s^{-1}.

Preparation of treatments

Sodium selenite (Na_2SeO_3) (99%, Sigma Aldrich, St. Louis, MO, USA) and Potassium iodate (KIO_3) (99%, Sigma Aldrich, St. Louis, MO, USA) and were used. A sodium selenite stock solution (1000 ppm) was prepared. A mass of 21.89 mg of Na_2SeO_3 was gauged to 10 mL with distilled water. Dilutions of 0.5, 1, 2 and 3 mL of the stock solution were gauged to 1 L with distilled water to obtain the treatments of 0.5, 1, 2, and 3 mg L^{-1}, respectively. Also a potassium iodate stock solution (1000 ppm) was prepared. A mass of 1.68 g of KIO_3 was gauged to 1 L with distilled water, and the dilutions of 100, 150, 200 and 250 mL of the stock solution were gauged to 1 L with distilled water to obtain the treatments of 100, 150, 200, and 250 mg L^{-1}, respectively. Control treatments consisted of imbibition in distilled water (Table 1).

Table 1. Imbibition treatments of tomato root with Se and I.

Na_2SeO_3 (mg L^{-1})	KIO_3 (mg L^{-1})

0	0
0.5	100
1	150
2	200
3	250

25 treatments (5^2 factorial), n = 4 replications, 100 experimental units.

Sowing and root priming

Saladette-type CID F1 (Harris Moran®, Davis, CA, USA) tomato seeds were sown in polystyrene trays with a substrate mixture of peat moss and perlite 1:1 (v/v). The seedling roots of tomato were primed in KIO_3 and Na_2SeO_3 osmotic solutions at the 35 days after sowing, and the seedling roots of the control treatment were primed in distilled water (Table 1), by a 24-h imbibition time.

Planting and crop management

Tomato seedlings were planted at the 36 days after sowing in 10-L plastic containers with a substrate mixture of peat moss and perlite 1:1 (v/v). Tomato plants were arranged into the greenhouse in a randomized complete block design with a factorial arrangement of two factors (KIO_3 and Na_2SeO_3) and five levels (concentrations in mg L^{-1}) (Table 1). Fertilization consisted of Steiner-type nutrient solution (Steiner, 1961) diluted in drip irrigation. The same substrate and fertigation conditions were used in the control, and KIO_3 and Na_2SeO_3 treatments to avoid another variation factor affecting the treatments performance.

Sampling

Samples of leaves and ripe fruits of tomato plants were obtained 120 days after planting. Leaf samples were collected from the leaf tissue of fully extended young leaves from 12 plants with four replications. Samples for biochemical analysis were collected from five ripe fruits per treatment, with a uniform color and size corresponding to stage six of ripening (USDA, 2017). Samples were stored at -80 °C, lyophilized in a 2.5 L FreeZone Benchtop Free Dry System freeze-dryer (LABCONCO, Kansas, MO, USA) and ground to a fine powder.

Non-enzymatic compounds

Vitamin C

The vitamin C content was determined by the 2,6 dichlorophenolindophenol titration method (Padayatty *et al*., 2001). The results were computed (Equation 1) and expressed in mg per 100 g of fresh tissue (mg 100 g^{-1} FW).

$$\text{Vitamin C} = \frac{\text{mL of 2,6 dichlorophenolindophenol} \times 0.088 \times \text{total volume} \times 100}{\text{aliquot volume} \times \text{sample weight}} \quad (1)$$

Phenols

Phenolic compounds were determined using the Folin–Ciocalteu method from the extraction with water:acetone according to Yu and Dahlgren (2000). The results were expressed in mg of gallic acid equivalents per gram of dry tissue (mg GAE g^{-1} DW).

Flavonoids

Flavonoids were determined by the Dowd method, adapted by Arvouet-Grand *et al*. (1994). The results were expressed in mg of quercetin equivalents per 100 g of dry tissue (mg QE 100 g^{-1} DW).

Chlorophyll

6

Chlorophyll content was quantified using the method proposed by Munira *et al*. (2015), by reading the absorbances at 663 and 645 nm wavelengths, and the results were computed (Equations 2, 3 and 4) and expressed in µg per gram of fresh tissue (µg g^{-1} FW).

$$Chlorophyll\ a = 3.64 \times A_{645} + 25.38 \times A_{663} \quad (2)$$

$$Chlorophyll\ b = 30.38 \times A_{645} - 6.58 \times A_{663} \quad (3)$$

$$Total\ chlorophyll = Chlorophyll\ a + Chlorophyll\ b \quad (4)$$

Lycopene and β-carotene

Lycopene and β-carotene contents were determined according to Nagata and Yamashita (1992), by reading the absorbances at 453, 505, 645, and 663 nm wavelengths. The results were computed (Equations 5 and 6) and expressed in mg per 100 g of dry tissue (mg 100 g^{-1} DW).

$$Lycopene = -0.0806 \times A_{453} + 0.372 \times A_{505} + 0.204 \times A_{645} - 0.0458 \times A_{663} \quad (5)$$

$$\beta\ carotene = 0.452 \times A_{453} - 0.304 \times A_{505} - 1.22 \times A_{645} + 0.216 \times A_{663} \quad (6)$$

Extraction

Samples of leaves and rape fruits of tomatoes were freeze-dried and macerated by using a mortar and pestle; 200 mg of dry tissue and 20 mg of polyvinyl pyrrolidone were added in a 2-mL centrifuge tube; 1.5 mL of phosphate buffer (0.1 M, pH 7-7.2) was added; and the mixture was subjected to sonication for 5 min, and then centrifuged in a Prism C2500 refrigerated microcentrifuge (Labnet International Inc., Edison, NJ, USA) at 12,500 rpm for 10 min at 4 °C. The supernatant was collected and filtered with a 0.45-mm-diameter nylon membrane. Finally, the supernatant was diluted (1:20) with phosphate buffer (0.1 M, pH 7-7.2). This dilution was used to analyze the absorbances of reduced glutathione (GSH), glutathione peroxidase (GPX), phenylalanine ammonium lyase (PAL), catalase (CAT), and ascorbate peroxidase (APX) in a GENESYS 10S UV-Vis Spectrum (Thermo Fisher Scientific, Inc., Waltham, MA, USA), as well as the antioxidant capacity of ABTS and DPPH radicals in a BK-EL10C Elisa microplate reader (BIOBASE, Jinan, Shandong, China) at the corresponding wavelengths.

Reduced Glutathione (GSH)

GSH quantification was performed by the spectrophotometric technique (Xue *et al*., 2001). The results were expressed in units per gram of total protein (U g^{-1} TP), where U is equal to mM of GSH equivalents per mL per minute of dry tissue (mM GSHE mL^{-1} min^{-1} DW).

Enzymatic Activity

Glutathione Peroxidase (GPX) (QE 1.11.1.9)

GPX was determined using the Flohé and Günzler (1984) method, adapted by Xue *et al*. (2001). The results were expressed in units per gram of total protein (U g^{-1} TP), where U is equal to mM of GSH equivalents per mL per minute of dry tissue (mM GSHE mL^{-1} min^{-1} DW).

Phenylalanine Ammonium Lyase (PAL) (QE 4.3.1.5)

PAL was determined according to Sykłowska-Baranek *et al*. (2012). The results were expressed in units per 100 g of total protein (U 100 g^{-1} TP), where U is equal to µmol of trans-cinnamic acid equivalents per mL per minute of dry tissue (µmol TCAE mL^{-1} min^{-1} DW).

Catalase (CAT) (QE 1.11.1.6)

CAT was determined by the spectrophotometric method Dhindsa *et al*. (1981). The results were expressed in units per gram of total protein (U g^{-1} TP), where U is equal to mM of H_2O_2 equivalents spent per mL per minute of dry tissue (mM H_2O_2E mL^{-1} min^{-1} DW).

Ascorbate Peroxidase (APX) (EC 1.11.1.11)

APX quantification was performed according to the Nakano and Asada, (1987) method. The results were expressed in units per gram of total protein (U g^{-1} TP), where U is equal to µmol of ascorbate oxidized equivalents per mL per minute of dry tissue (µmol AOE mL^{-1} min^{-1} DW).

Antioxidant Capacity

Hydrophilic and Lipophilic Compounds by ABTS

Antioxidant activity by the ABTS radical (2,2′-azino-bis-3-ethylbenzothiazolin-6-sulfonic acid) was determined by the spectrophotometric method (Re *et al*., 1999). Both the antioxidant capacity results of hydrophilic and lipophilic compounds by ABTS were expressed in µmol of Trolox equivalents per gram of dry tissue (µmol TE g^{-1} DW).

Hydrophilic Compounds by DPPH

Antioxidant capacity by DPPH radical (2,2-Diphenyl-1-picrylhydrazyl) was performed according to Brand–Williams *et al*. (1995). The antioxidant capacity results of hydrophilic compounds by DPPH were expressed in µmol of Trolox equivalents per gram of dry tissue (µmol TE g^{-1} DW).

Statistical Analyses

The results were analyzed by analysis of variance to determine the variables that presented a significant statistical difference ($p \leq 0.05$) so that the variables with significant effects were submitted to comparison means tests by Tukey ($p \leq 0.05$) using the statistical software InfoStat® 2020e.

Results and Discussion

Non-enzymatic compounds in tomato fruits by Na_2SeO_3

Regarding the sodium selenite factor in the tomato fruits, the GSH content significantly increased 5.6 times in the dose of 3 mg L^{-1}, while the vitamin C content significantly decreased in the doses of 0.5, 1 and 2 mg L^{-1}, in relation to the control treatments. On the other hand, the total phenols content significantly increased by 4 and 9% in the doses of 0.5 and 3 mg L^{-1} in relation to the control treatment, similar results were reported by Abedi *et al*. (2021) and Andrejiová *et al*. (2016), who indicated that the use of selenium favors the increase of polyphenols in the tomato crop. The flavonoid, lycopene and β-carotene contents significantly increased by 22, 52 and 127%, respectively, in the dose of 0.5 mg L^{-1} in relation to the control treatments (Figure 1), similar results were reported by Rady *et al*. (2020), who indicated that the use of selenium favors the increase in the lycopene content in tomato fruits, while Gaucin-Delgado *et al*. (2020) and Sabatino *et al*. (2021) indicated that the use of selenium presents important aspects in the nutraceutical quality in tomato fruits, presenting increases in the carotenoid, polyphenol, vitamin C and lycopene contents.

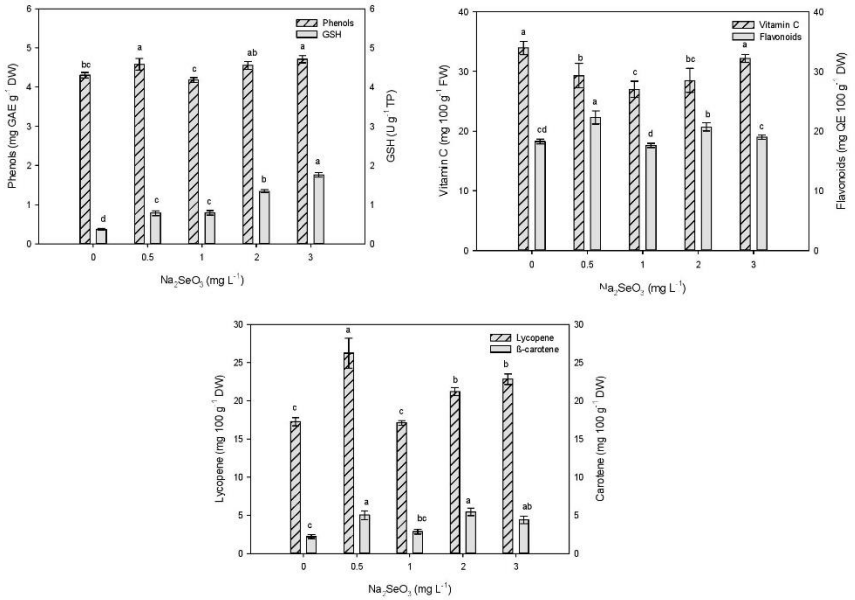

Figure 1. Effect of root imbibition by Na_2SeO_3 in the non-enzymatic antioxidant compounds in tomato fruits. Different letters indicate significant differences between treatments (Tukey HSD, $p \leq 0.05$). n = 4.

Non-enzymatic compounds in tomato fruits by KIO_3

The root imbibition with potassium iodate significantly influenced the contents of non-enzymatic compounds in the tomato fruits. The GSH and vitamin C contents increased by 37 and 11.7%, respectively, in the dose of 200 mg L^{-1}, in relation to the corresponding control treatments. Li *et al*. (2017a) reported that the use of iodine concentrations favors the increase in vitamin C content in chili crop, which tends to decrease at high iodine concentrations. This stimulation effect of iodine at low concentrations to increase the vitamin C content also was observed in strawberry crop by Li *et al*. (2017b) with applications either as iodide or iodate in the nutrient solution in concentrations lower than 1 mg L^{-1}, while higher iodine concentrations influenced the decrease the ascorbic acid content in relation to the control treatment. The phenols, flavonoids and lycopene contents increased in the dose of 200 mg L^{-1}, while the β-carotene content was not significantly affected in relation to the control treatments (Figure 2). Opposite results were reported by Smoleń *et al*. (2015), where the use of KI and KIO_3 did not significantly influence the carotenoids, flavonoids and phenols contents in relation to the control treatments.

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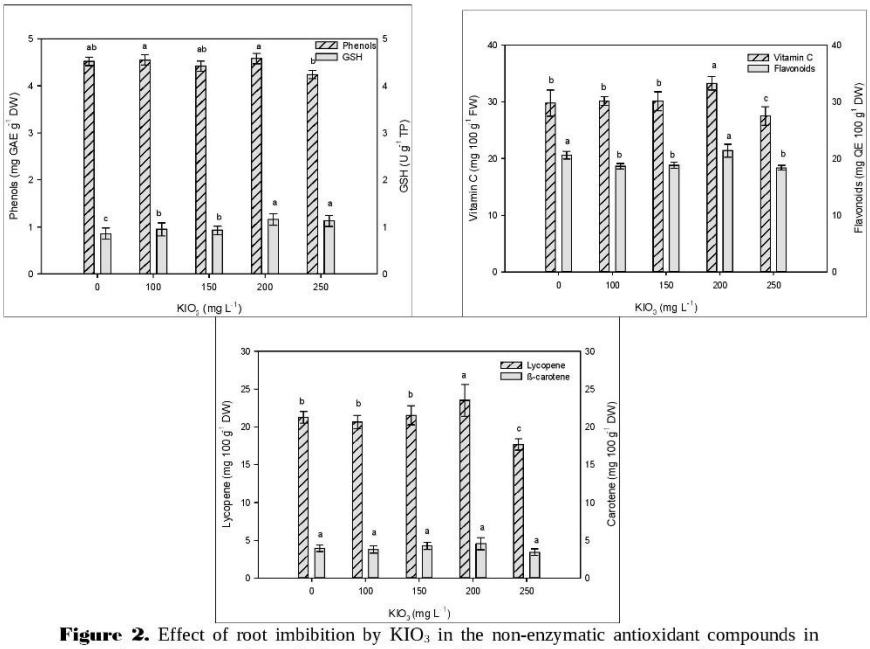

251
252 **Figure 2.** Effect of root imbibition by KIO_3 in the non-enzymatic antioxidant compounds in
253 tomato fruits. Different letters indicate significant differences between treatments (Tukey HSD, p
254 ≤ 0.05). n = 4.
255
256 *Non-enzymatic compounds in tomato fruits by Na_2SeO_3 and KIO_3 interactions*
257 The GSH content in the tomato fruits significantly increased 9 times in the 3-100 mg L^{-1}
258 interaction, in relation to the control treatment (0-0 mg L^{-1} interaction). The vitamin C content tended
259 to significant decrease by 56.4% of in the 2-250 mg L^{-1} in relation to the 2-0 mg L^{-1} interaction implies
260 that KIO_3 have a negative effect in the ascorbic acid content when it is combined with Na_2SeO_3 at 2
261 mg L^{-1}. The 0.5-200 mg L^{-1} interaction significantly influenced the increase of phenols, flavonoids,
262 lycopene and β-carotenes contents in 1.23, 1.66, 2.13 and 2.76 times, respectively, in relation to the
263 control treatments (Table 2), for which this interaction presents important aspects in nutraceutical
264 quality and postharvest quality, because the flavonoid contributes to delay the ripening of tomato fruits
265 (Zhang *et al*., 2015).
266
267 **Table 2.** Effect of root imbibition by Na_2SeO_3 and KIO_3 interactions in the non-enzymatic
268 antioxidant compounds in tomato fruits.

Na_2SeO_3 (mg L^{-1})	KIO_3 (mg L^{-1})	GSH (U g^{-1} TP)	Vitamin C (mg 100 g^{-1} FW)	Phenols (mg AG g^{-1} DW)	Flavonoids (mg QE 100 g^{-1} DW)	Licopene (mg 100 g^{-1} DW)	β-carotene (mg 100 g^{-1} DW)
0	0	0.2k	37.0abc	4.3bcde	18.6defghi	17.6ghijk	2.9b
0	100	0.3jk	28.4def	4.4abcde	16.4hi	17.6ghijk	1.8b
0	150	0.3jk	39.1a	3.8de	18.1defghi	16.1jk	2.0b
0	200	0.4ijk	34.2abcd	4.3bcde	20.6cdef	19.7efghijk	1.7b
0	250	0.5ij	30.7cdef	4.4abcde	17.4fghi	15.0k	2.4b
0.5	0	0.5i	15.8h	4.4abcde	20.0cdefg	25.5bc	4.1ab
0.5	100	0.6hi	32.3bcde	4.4abcde	19.6cdefgh	23.6cdef	4.2ab
0.5	150	0.8gh	31.1cdef	4.9abc	22.5bc	28.9b	6.5ab
0.5	200	1.2de	38.6ab	5.3a	30.9a	37.4a	8.0a

0.5	250	0.6ghi	28.4def	3.7e	18.1defghi	15.4jk	2.1b
1	0	0.5ij	24.6fg	4.1cde	17.9defghi	17.9ghijk	1.7b
1	100	0.5ij	26.7efg	3.9de	16.0i	17.3hijk	2.6b
1	150	0.8fg	21.1gh	4.2cde	17.9defghi	17.0ijk	3.5ab
1	200	0.8fg	36.0abc	4.4abcde	19.0defghi	15.6jk	3.0b
1	250	1.1de	26.4efg	4.1cde	16.9ghi	17.5ghijk	3.3ab
2	0	1.5b	39.0a	5.1ab	25.2b	22.5cdefg	6.4ab
2	100	1.3bcd	28.9def	4.6abcde	20.5cdef	20.1defghij	5.9ab
2	150	1.1ef	30.8cdef	4.4bcde	17.5fghi	22.2cdefgh	4.1ab
2	200	1.2cde	26.5efg	4.4bcde	18.7defghi	19.3efghijk	5.7ab
2	250	1.4bc	17.0h	4.2cde	21.3cd	21.6cdefghi	4.9ab
3	0	1.3bcd	32.3bcde	4.5abcde	21.0cde	22.5cdefg	4.3ab
3	100	1.8a	34.1abcd	5.3a	20.5cdef	24.4bcde	4.1ab
3	150	1.5b	28.3def	4.6 abcd	17.7efghi	23.2cdef	4.9ab
3	200	2.0a	31.1cdef	4.3bcde	17.5fghi	25.2bcd	4.2ab
3	250	1.9a	34.7abcd	4.6abcd	17.9defghi	18.6fghijk	4.1ab

Different letters within the columns indicate significant differences between treatments (Tukey HSD, $p \leq 0.05$). n = 4.

Enzymatic compounds in tomato leaves by Na_2SeO_3

The seedling root imbibition with sodium selenite significantly influenced the increase of the GSH content in tomato leaves, to a maximum increase of four times in the dose of 3 mg L^{-1} in relation to the control treatment. Rady *et al*. (2020) found that the use of selenium influence the increase of GSH content in tomato seedlings, while Dall'Acqua *et al*. (2019) indicated that the use of exogenous selenium may influence the GSH content according to the crop specie and the application dose. The phenol content significantly increased 3.5 times in the dose of 3 mg L^{-1} in relation to the control treatment. The flavonoid content were not significantly modified by Na_2SeO_3 (Figure 3), Zhang *et al*. (2023) also reported not significant results in the flavonoid content with Na_2SeO_3 applied by foliar spraying and through irrigation. The chlorophyll contents significantly decreased in the dose of 0.5 mg L^{-1} in relation to the control treatments. Huang et al. (2018), Khalofah *et al*. (2021), and El-Badri *et al*. (2022), also reported the decrease in chlorophyll and β-carotene contents as the Na_2SeO_3 concentration was higher; however, Alsamadany *et al*. (2023) indicated that the use of selenium favored the increase in the chlorophyll content, while the β-carotene content were not significantly modified, in relation to the control treatments. Cunha *et al*. (2022) and Ishtiaq *et al*. (2023) indicated that the use of selenium influence the increase of chlorophyll, β-carotene and phenolic compounds with concentrations from 7.5 to 15 μg kg^{-1}, whereas the selenium concentration was higher the content of the variables began to decrease. The Se at low concentrations decreases the leaf senescence rate and the peroxidase activity, which can increase the nitrogen utilization efficiency and benefiting the crop production. However, in high concentrations the Se promotes oxidative stress, nutritional disturbance, damaging photosynthesis (da Cruz Ferreira *et al*., 2020), inducing symptoms of toxicity in the plant, reducing growth, causing foliar chlorosis and small and brittle roots (de Mello Prado, 2021).

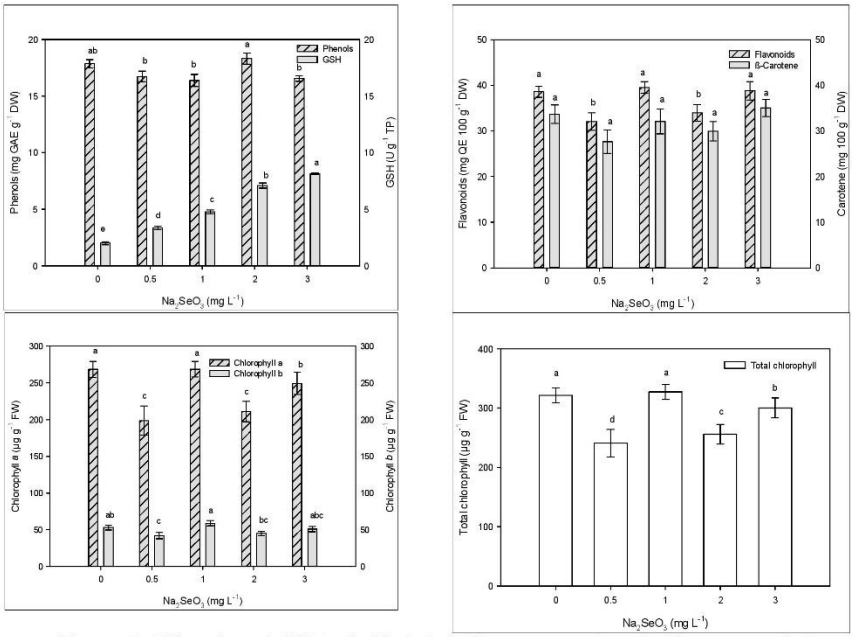

Figure 3. Effect of root imbibition by Na_2SeO_3 in the non-enzymatic antioxidant compounds in tomato leaves. Different letters indicate significant differences between treatments (Tukey HSD, $p \leq 0.05$). n = 4.

Non-enzymatic compounds in tomato leaves by KIO_3

In the tomato leaves the potassium iodate significantly influenced an increase of 26% of the GSH content in the dose of 250 mg L^{-1}, in relation to the control treatment. The phenol content was not significantly modified by KIO_3, similar results are those reported by Puccinelli *et al*. (2021) who indicated that the use of KI in the lettuce crop did not a significant influence the phenol content. The flavonoid content significantly increased by 9.8% in the dose of 100 mg L^{-1} of KIO_3 in relation to the control treatment. The greater chlorophyll contents were presented in the dose of 100 mg L^{-1} of KIO_3 in relation to the control treatments, these results agree with those reported by Li *et al*. (2017a) who indicated that the use of iodine improves the chlorophyll content, however, as the iodine concentration increases, the chlorophyll content begins to decrease. Regarding the β-carotene content, there was no significant difference between the treatments (Figure 4). Krzepilko *et al*. (2023) indicated that the use of iodine influences the increase in the chlorophyll content, however, in the carotenoid content, the applications either as KI or KIO_3 do not influence the carotenoid content.

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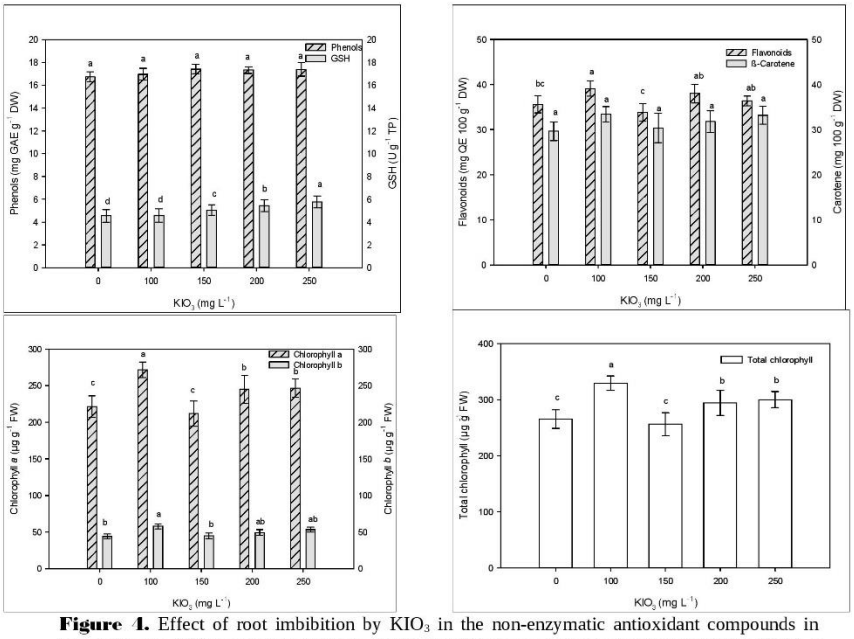

312
313 **Figure 1.** Effect of root imbibition by KIO_3 in the non-enzymatic antioxidant compounds in
314 tomato leaves. Different letters indicate significant differences between treatments (Tukey HSD, p
315 ≤ 0.05). n = 4.
316
317 *Non-enzymatic compounds in tomato leaves by Na_2SeO_3 and KIO_3 interactions*
318 The higher significant GSH content in the tomato leaves reached 7.25 times in the 2-250 mg L^{-1}
319 (Na_2SeO_3 - KIO_3) interaction in relation to the control treatment (0-0 mg L^{-1} interaction), which
320 evidences the importance of the glutathione role in the control of reactive oxygen species (ROS) that
321 accumulate during biotic stress, and the GSH reduces the cell damage (Gullner *et al*., 2017;
322 Zechmann, 2020). The phenol and β-carotene contents in the tomato leaves did not show significant
323 effects. Regarding the flavonoid content, the tomato leaves reached an increase of 41.2% in the 0.5-
324 100 mg L^{-1} interaction, and 51.8% in the 3-200 mg L^{-1} interaction, in relation to the control treatment,
325 however the 10.5% surplus implies an increase in the cost by 6(Na_2SeO_3) + 2(KIO_3). Golubkina *et al*.
326 (2018) reported that the use of iodine and selenium together influence favorable effects by increasing
327 the content of flavonoids, while Smoleń *et al*. (2019) indicated that the application of iodine and
328 selenium together influence the increase of plant metabolism, which is reflected in the increase of
329 antioxidant compounds in the face of the stress by which the plants are found. The chlorophyll-*a*,
330 chlorophyll-*b* and total chlorophyll contents significantly increased by 34, 80.6 and 40.9%,
331 respectively, in the 1-100 mg L^{-1} interaction, compared to the control treatments (Table 3).
332 **Table 3.** Effect of root imbibition by Na_2SeO_3 and KIO_3 interactions in the non-enzymatic
333 antioxidant compounds in tomato leaves.

Na_2SeO_3 (mg L^{-1})	KIO_3 (mg L^{-1})	GSH (U g^{-1} TP)	Phenols (mg AG g^{-1} DW)	Flavonoids (mg QE 100 g^{-1} DW)	Chl-*a* (µg g^{-1})	Chl-*b* (µg g^{-1})	Total Chl. (µg g^{-1})	β carotene (mg 100 g^{-1} DW)
0	0	1.2i	17.3abc	31.3efghi	231.3efg	40.2b-e	271.5fg	29.5a
0	100	1.4hi	17.3abc	42.8ab	309.3ab	62.9ab	372.2a	35.2a
0	150	2.1gh	17.3abc	43.2ab	298.3abc	60.5abc	358.9abc	38.6a
0	200	2.2gh	18.1abc	41.8abc	300.8abc	57.4a-d	358.3a-d	33.7a
0	250	2.9g	19.1ab	33.5cdefgh	201.6fgh	44.4a-e	246.0gh	31.1a
0.5	0	2.8g	16.4abc	29.7ghi	162.4h-k	36.3b-e	198.7ij	24.4a
0.5	100	2.2gh	15.8abc	44.2ab	284.8a-d	59.5abc	344.3a-d	36.7a

0.5	150	3.9f	19.0ab	24.3i	118.9kl	26.4de	145.3k	19.5a
0.5	200	3.8f	17.4abc	23.7i	111.5l	24.4e	135.9k	19.8a
0.5	250	3.8f	14.8bc	38.0bcdefg	315.9a	62.8abc	378.8a	37.6a
1	0	4.0f	14.1c	45.8ab	298.9abc	63.2ab	362.2ab	31.8a
1	100	4.2f	15.4abc	42.3abc	309.9ab	72.6a	382.5a	31.8a
1	150	4.6ef	17.3abc	37.5bcdefg	268.6a-e	55.2a-e	323.9b-e	34.7a
1	200	5.4de	17.0abc	32.5defghi	184.8ghi	40.7b-e	225.5hi	30.0a
1	250	5.4de	17.9abc	39.3abcdef	280.2a-d	62.3abc	342.6a-d	31.7a
2	0	6.2cd	18.9ab	26.6hi	139.6i-l	31.7b-e	171.3jk	22.4a
2	100	6.7c	19.5[a]	27.6hi	189.8gh	39.6b-e	229.4hi	28.0a
2	150	6.6c	16.9abc	40.3abcd	240.6def	50.2a-e	290.8ef	34.3a
2	200	7.1bc	16.7abc	44.4ab	310.6ab	62.7abc	373.4a	36.6a
2	250	8.7a	19.2ab	30.6fghi	174.1hij	39.8b-e	214.0hi	28.1a
3	0	8.3a	16.7abc	44.3ab	275.0a-e	48.5a-e	323.5b-e	39.8a
3	100	8.1a	16.6abc	38.2b-g	262.7b-e	55.4a-e	318.2de	35.0a
3	150	7.8ab	16.3abc	23.7i	131.9jkl	31.2cde	163.1jk	24.3a
3	200	8.5a	17.2abc	47.5a	316.2a	61.3abc	377.5a	38.6a
3	250	7.9ab	15.8abc	40.1abcde	261.0cde	58.0a-d	319.0cde	37.2a

Different letters within the columns indicate significant differences between treatments (Tukey HSD, $p \leq 0.05$). n = 4.

Enzymatic compounds of tomato fruits by Na_2SeO_3

The sodium selenite applied by imbibition to the seedling roots negatively influenced the enzymatic activity in the tomato fruits. The GPX, PAL, CAT y APX enzymatic activities significantly decreased by 73.1, 68.1, 85.3 and 73.9%, respectively, in the dose of 3 mg L^{-1} in relation of the control treatments (Figure 5), which indicates that Na_2SeO_3 applications by root imbibition influence toxicity problems by inhibiting the enzymatic activities, because the ROS concentrations exceed the cellular detoxification capacity, cause oxidative stress, increase the oxidation of molecules such as DNA, proteins, lipids and carbohydrates (Berni *et al*., 2019; Sali *et al*., 2018). An alternative for improving the enzymatic activity in tomato cultivation from the root priming is the use of Se nanoparticles (Ishtiaq *et al*., 2023).

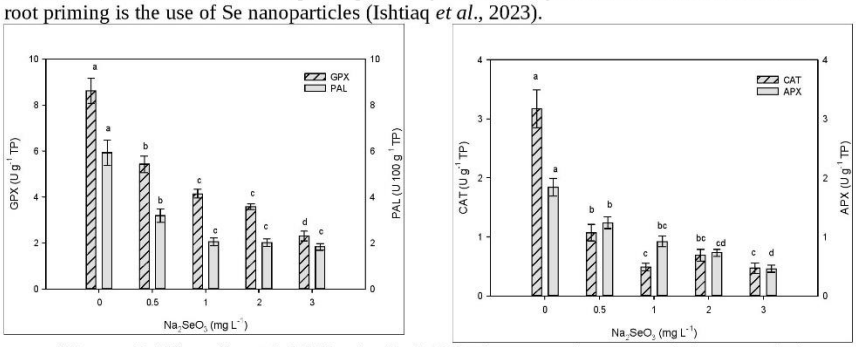

Figure 5. Effect of root imbibition by Na_2SeO_3 in the enzymatic compounds in tomato fruits. Different letters indicate significant differences between treatments (Tukey HSD, $p \leq 0.05$). n = 4.

Enzymatic compounds of tomato fruits by KIO_3

The potassium iodate applied by imbibition to the seedling roots negatively influenced the enzymatic activity in the tomato fruits. The GPX, PAL, CAT y APX enzymatic activities significantly decreased by 23.8, 42.5, 53.1 and 33.3%, respectively, in the dose of 250 mg L^{-1} in relation of the control treatments (Figure 6). The CAT and APX enzymes are responsible for degrading H_2O_2 in water, such process was inhibited due to enzymatic activity was decreased as the KIO_3 dose increased.

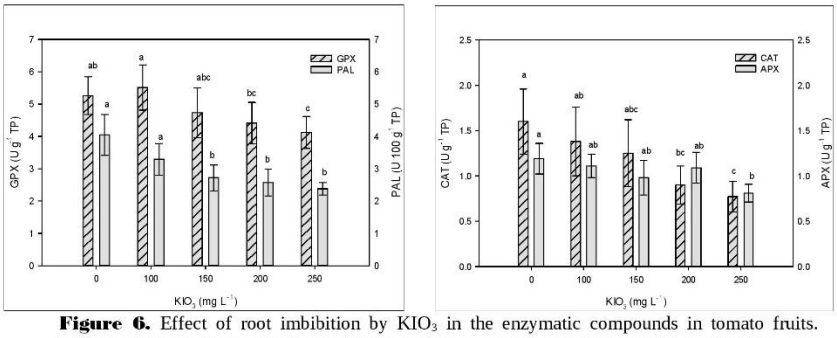

Figure 6. Effect of root imbibition by KIO_3 in the enzymatic compounds in tomato fruits. Different letters indicate significant differences between treatments (Tukey HSD, $p \leq 0.05$). n = 4.

Enzymatic compounds of tomato fruits by Na_2SeO_3 and KIO_3 interactions

The enzymatic activity in the tomato fruits significantly decreased as the doses of treatments of Na_2SeO_3 and KIO_3 interaction increased (Table 4). The enzymes in the plant reduce the level of reactive oxygen species (ROS), where catalase degrades H_2O_2 into oxygen and water, while ascorbate peroxidase uses ascorbic acid as a donor to stimulate the H_2O_2 degradation, while reduced glutathione is responsible for the production of ascorbic acid (Hussain *et al*., 2019; Zhu *et al*., 2017).

Table 4. Effect of root imbibition by Na_2SeO_3 and KIO_3 interactions in the enzymatic compounds in tomato fruits.

Na_2SeO_3 (mg L^{-1})	KIO_3 (mg L^{-1})	PAL (U 100 g^{-1} TP)	GPX (U g^{-1} TP)	CAT (U g^{-1} TP)	APX (U g^{-1} TP)
0	0	8.8a	7.2abc	4.1a	1.9ab
0	100	7.0ab	10.0a	3.9a	1.8abc
0	150	5.5bc	10.0a	3.6ab	2.1a
0	200	4.9bcd	8.5ab	2.2bc	1.9ab
0	250	3.1cde	7.1abc	1.8cd	1.3abcde
0.5	0	4.0cde	7.1abc	1.6cd	1.7abcd
0.5	100	3.2cde	6.3bcd	1.1cd	1.0abcde
0.5	150	2.7cde	4.5cde	1.0cd	0.9bcde
0.5	200	3.5cde	4.7cde	0.8cd	1.3abcde
0.5	250	2.4de	4.3cde	0.7cd	1.0abcde
1	0	2.5de	4.7cde	0.4d	1.1abcde
1	100	2.0e	4.8cde	0.5d	1.2abcde
1	150	1.9e	3.9de	0.5d	0.8cde
1	200	1.1e	3.1de	0.5d	0.6de
1	250	2.5de	4.1cde	0.4d	0.7cde
2	0	2.1de	3.5de	1.1cd	0.6de
2	100	2.1de	3.8de	0.6d	0.8bcde
2	150	1.9e	3.3de	0.5d	0.6de
2	200	1.4e	3.9de	0.5d	0.9bcde
2	250	2.4de	3.3de	0.6cd	0.5e
3	0	2.6de	3.6de	0.7cd	0.5e
3	100	1.9e	2.5e	0.6cd	0.5e
3	150	1.4e	1.8e	0.3d	0.3e
3	200	1.7e	1.7e	0.3d	0.5de
3	250	1.3e	1.6e	0.2d	0.3e

Different letters within the columns indicate significant differences between treatments (Tukey HSD, $p \leq 0.05$). n = 4.

Enzymatic compounds of tomato leaves by Na_2SeO_3

The sodium selenite applied by imbibition to the seedling roots negatively influenced the enzymatic activity in the tomato leaves. The GPX, PAL, CAT y APX enzymatic activities significantly decreased by 50, 75, 70 and 97.7%, respectively, in the dose of 3 mg L^{-1} in relation of the control treatments (Figure 7). Rady *et al*. (2020) indicated that the use of Na_2SeO_3 at 25

and 50 mM applied by foliar spraying influence the increase of enzymatic activity, while Cunha *et al*. (2022) reported an increase in the CAT and APX enzymatic activities in the lowest concentration (7.5 µg kg^{-1}), and as the concentration increased the enzyme activities decreased.

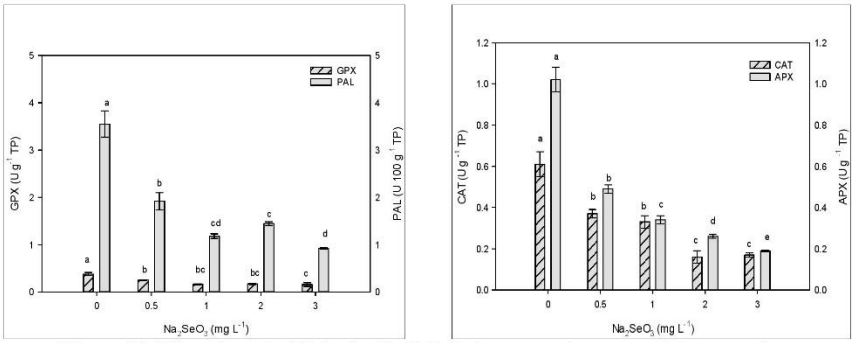

Figure 7. Effect of root imbibition by Na_2SeO_3 in the enzymatic compounds in tomato leaves. Different letters indicate significant differences between treatments (Tukey HSD, $p \leq 0.05$). n = 4.

Enzymatic compounds of tomato leaves by KIO_3

The potassium iodate applied by imbibition to the seedling roots negatively influenced the enzymatic activity in the tomato leaves. The GPX, PAL, CAT y APX enzymatic activities significantly decreased by 2.3, 34.1, 11.5 and 31.7%, respectively, in the dose of 250 mg L^{-1} in relation of the control treatments (Figure 8), which reflects that in higher concentrations the iodine presents an oxidative stress, due to the CAT and APX are enzymatic antioxidants can catalyze the decomposition of H_2O_2 into H_2O and O_2, which protect the cells from excess H_2O_2. Li *et al*. (2017a) reported that as higher the iodine concentration in seedlings, the enzymatic activity is lower in relation of the control treatment.

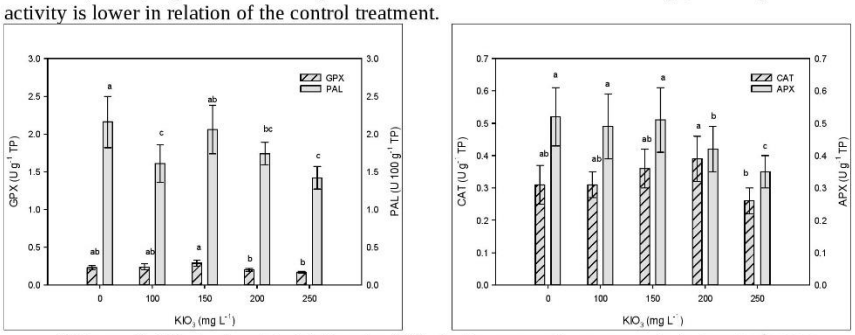

Figure 8. Effect of root imbibition by KIO_3 in the enzymatic compounds in tomato leaves. Different letters indicate significant differences between treatments (Tukey HSD, $p \leq 0.05$). n = 4.

Enzymatic compounds of tomato leaves by Na_2SeO_3 and KIO_3 interactions

The enzymatic activity in the tomato leaves significantly decreased as the concentrations of the treatments of the Na_2SeO_3 and KIO_3 Interactions were increased (Table 5).

Table 5. Effect of root imbibition by Na_2SeO_3 and KIO_3 interactions in the enzymatic compounds in tomato leaves.

Na_2SeO_3 (mg L^{-1})	KIO_3 (mg L^{-1})	PAL (U 100 g^{-1} TP)	GPX (U g^{-1} TP)	CAT (U g^{-1} TP)	APX (U g^{-1} TP)

0	0	4.6[a]	0.4abc	0.59abc	1.17[a]
0	100	3.7ab	0.5[a]	0.5abcd	1.17[a]
0	150	4.3[a]	0.4ab	0.68ab	1.17[a]
0	200	2.4cde	0.3abcd	0.84[a]	0.89b
0	250	2.6bc	0.2bcd	0.44bcde	0.69c
0.5	0	2.4cde	0.2abcd	0.38bcdef	0.51cde
0.5	100	1.1f	0.2bcd	0.29cdef	0.51cde
0.5	150	2.5bcd	0.3abcd	0.36bcdef	0.53cd
0.5	200	2.5bcd	0.2bcd	0.44bcde	0.5cde
0.5	250	0.9f	0.1bcd	0.37bcdef	0.4defg
1	0	0.9f	0.1bcd	0.33bcdef	0.44def
1	100	0.9f	0.1cd	0.37bcdef	0.34defgh
1	150	1.2ef	0.2bcd	0.46bcde	0.33defgh
1	200	1.4cdef	0.1cd	0.24cdef	0.32efgh
1	250	1.3def	0.1cd	0.23def	0.25gh
2	0	1.7cdef	0.1bcd	0.08f	0.28fgh
2	100	1.4cdef	0.1bcd	0.24cdef	0.26fgh
2	150	1.3def	0.1bcd	0.19def	0.32efgh
2	200	1.3def	0.1d	0.2def	0.23gh
2	250	1.3def	0.1cd	0.07f	0.21gh
3	0	1.0f	0.1d	0.19def	0.2h
3	100	0.8f	0.1d	0.15def	0.19h
3	150	0.8f	0.3abcd	0.1ef	0.18h
3	200	0.9f	0.1d	0.21def	0.17h
3	250	0.8f	0.1d	0.18def	0.2h

Different letters within the columns indicate significant differences between treatments (Tukey HSD, $p \leq 0.05$). n = 4.

Antioxidant capacity of tomato fruits and leaves by Na_2SeO_3

The sodium selenite positively influenced the antioxidant capacity in tomato fruits. The hydrophilic compounds by ABTS and by DPPH radicals increased by 55.6 and 18.4%, respectively, in the dose of 3 mg L^{-1} in relation to the control treatments (Figure 9a). The lipophilic compounds by ABTS radical in tomato fruits were not significantly influenced by Na_2SeO_3.

The sodium selenite negatively influenced the antioxidant capacity in tomato leaves. The hydrophilic and lipophilic compounds by ABTS radical decreased by 35.1 and 66.7%, respectively, in the dose of 3 mg L^{-1} in relation to the control treatments (Figure 9b). The hydrophilic compounds by DPPH radical in tomato leaves were not significantly influenced by Na_2SeO_3. Saeedi *et al*. (2021) reported that the exogenous application of selenium presented favorable aspects in the antioxidant activity, as well as the improvement of secondary metabolites in cauliflower crop.

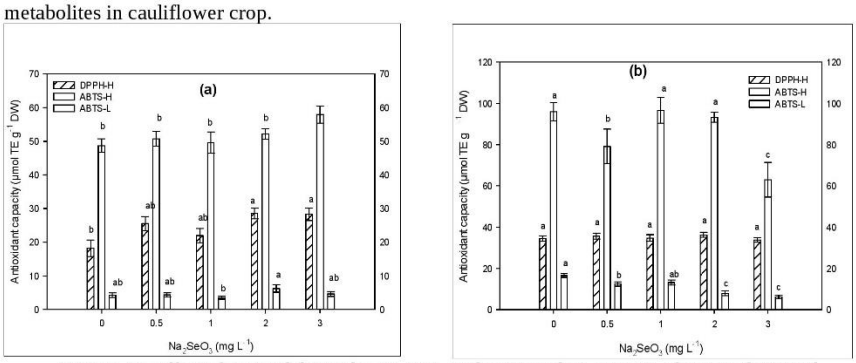

Figure 9. Effect of root imbibition by Na_2SeO_3 in the antioxidant capacity of tomato fruits and leaves. Different letters indicate significant differences between treatments (Tukey HSD, $p \leq 0.05$). n = 4.

Antioxidant capacity of tomato fruits and leaves by KIO_3

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The antioxidant capacity of hydrophilic compounds by ABTS radical influenced by potassium iodate, significantly increased in the tomato fruits by 17.7% (Figure 10a) and significantly decreased in the tomato leaves by 20.5% (Figure 10b) both the two in the dose of 250 mg L^{-1} in relation to the control treatments. The lipophilic compounds by ABTS radical and the hydrophilic compounds by DPPH radical in tomato fruits and leaves were not significantly influenced by KIO_3. Medrano Macías *et al*. (2021) obtained statistical difference in the antioxidant capacity of strawberry with KIO_3 by the hydrophilic ABTS method, while the lipophilic ABTS and DPPH methods there were no effected. Sarrou *et al*. (2019) and Smoleń *et al*. (2015) reported that the use of KI and KIO_3 does not present an effect on the antioxidant capacity.

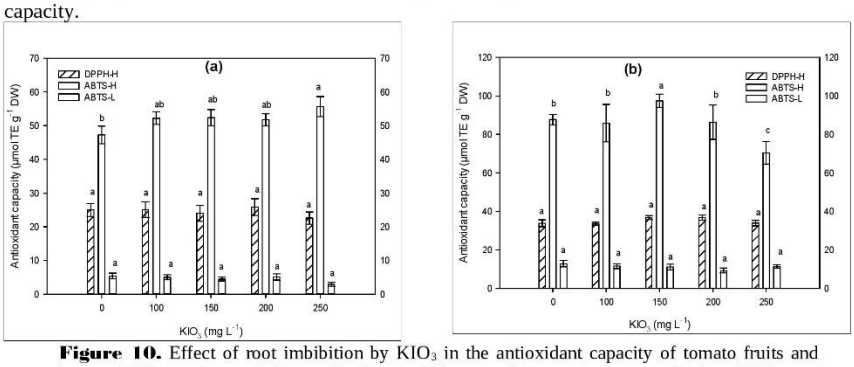

Figure 10. Effect of root imbibition by KIO_3 in the antioxidant capacity of tomato fruits and leaves. Different letters indicate significant differences between treatments (Tukey HSD, $p \leq 0.05$). n = 4.

Antioxidant capacity of tomato fruits and leaves by Na_2SeO_3 and KIO_3 interactions

The antioxidant capacity of the fruits by the hydrophilic ABTS method, presented differences where the treatment of 3-250 mg L^{-1}, presented a greater antioxidant capacity in comparison with the treatment of 1 mg L^{-1} of Na_2SeO_3, as well as with the control. The lipophilic ABTS method did not present an effect between the treatments. The DPPH method presented a negative effect in the treatments of 200 and 250 mg L^{-1} of KIO_3, which are the treatments with the lowest antioxidant capacity in tomato fruits (Table 6).

In the leaves, the antioxidant capacity presented an effect through hydrophilic ABTS, where the 1-100 mg L^{-1}, obtained a greater antioxidant capacity compared to the treatment of 0.5-100 mg L^{-1}, which was the treatment where there was a lower antioxidant activity in the leaves of the plant. In the lipophilic ABTS method, there was an effect in the control, where there was a higher antioxidant capacity compared to the treatment of 3-150 mg L^{-1}, on the other hand, by means of hydrophilic DPPH, an effect was presented in the 0.5-200 mg L^{-1} treatment, where a greater antioxidant capacity was obtained by this method, while the antioxidant capacity was affected with the use of 1 mg L^{-1} of Na_2SeO_3 (Table 6).

Table 6. Effect of root imbibition by Na_2SeO_3 and KIO_3 interactions in the antioxidant capacity (µmol TE g^{-1} DW) of tomato fruits and leaves.

Na_2SeO_3 (mg L^{-1})	KIO_3 (mg L^{-1})	Fruto ABTS-H	Fruto ABTS-L	Fruto DPPH-H	Hoja ABTS-H	Hoja ABTS-L	Hoja DPPH-H
0	0	54.7bcdef	7.8[a]	27.4ab	90.9cdef	20.4[a]	34.9abcd
0	100	50.2cdef	2.0a	28.5ab	88.9cdef	17.0abc	33.0abcd
0	150	46.2defg	6.6[a]	10.0b	81.6def	19.0ab	38.7abc
0	200	40.9efg	2.7[a]	10.7b	131.4ab	11.5abcdef	30.4bcd
0	250	51.4cdef	1.9[a]	14.3ab	86.5cdef	14.4abcdef	34.9abcd
0.5	0	40.2fg	3.0a	17.9ab	93.2cdef	12.4abcdef	35.8abc

0.5	100	56.9bcde	8.4[a]	24.3ab	11.3g	15.7abcd	30.1bcd
0.5	150	51.5bcdef	3.9[a]	27.3ab	111.1abc	11.9abcdef	40.6ab
0.5	200	62.7abc	3.7[a]	37.0a	104.5bcd	14.2abcdef	43.1[a]
0.5	250	42.1efg	2.4[a]	20.8ab	75.4ef	7.7bcdef	28.7bcd
1	0	31.1g	2.8[a]	15.8ab	70.4f	12.4abcdef	23.0d
1	100	42.0efg	3.0a	17.2ab	135.6[a]	14.0abcdef	32.8abcd
1	150	67.9ab	4.4[a]	25.5ab	105.7bc	14.6abcde	37.5abc
1	200	52.6bcdef	4.6[a]	23.4ab	95.9cdef	11.9abcdef	40.5ab
1	250	54.3bcdef	2.7[a]	27.7ab	74.9ef	12.9abcdef	39.4abc
2	0	59.0bcd	9.0a	33.8[a]	101.6cde	9.9abcdef	37.1abc
2	100	53.1bcdef	4.7[a]	29.3ab	100.8cde	7.8bcdef	37.2abc
2	150	45.6defg	3.0a	26.7ab	88.6cdef	6.8cdef	31.6abcd
2	200	50.6cdef	9.2[a]	25.3ab	83.8cdef	3.5ef	36.7abc
2	250	52.4bcdef	5.1[a]	27.4ab	91.3cdef	11.6abcdef	38.3abc
3	0	51.2cdef	3.9[a]	29.9ab	82def	9.0abcdef	38.0abc
3	100	58.5bcd	6.7[a]	26.0ab	92.3cdef	3.2ef	34.3abcd
3	150	50.3cdef	4.2[a]	30.3ab	100.3cde	2.9f	35.2abc
3	200	51.7bcdef	5.2[a]	32.5ab	16.1g	5.1def	33.0abcd
3	250	77.6[a]	2.7[a]	22.5ab	23.7g	10.4abcdef	28.2cd

Different letters within the columns indicate significant differences between treatments (Tukey HSD, $p \leq 0.05$). n = 4.

Conclusions

The application of KIO_3 and Na_2SeO_3 in root imbibition in tomato cultivation presents important aspects in the increase of non-enzymatic compounds such as vitamin C, phenols, flavonoids and reduced glutathione, as well as in antioxidant capacity; however, this method presented an inhibition in the evaluated antioxidant enzymes.

Authors' Contributions

Conceptualization: FMR and AMM; Data curation: FMR and AMM; Formal analysis: ABM and AMM; Methodology: FMR and AMM; Resources: AMM, ABM and SGM; Software: FMR and AMM; Supervision: AJM, ABMD and FMLV; Visualization: AJM, ABMD and FMLV; Writing - original draft: FMR and AMM; Writing - review and editing: FMR and AMM. All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Does not apply.

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Conflict of Interests

The authors declare no conflict of interest.

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CONCLUSIÓN GENERAL

En el presente trabajo de investigación se reporta que el uso de los tratamientos de imbibición en semillas como en raíz en plántulas con yodato de potasio y selenito de sodio en el cultivo de tomate presenta aspectos importantes en la concentración de compuestos antioxidante, sin embargo, en la forma de aplicación, por raíz presentó una inhibición en la actividad enzimática de las variables evaluadas, por lo tanto el establecimiento de una dosis óptima para este método es una alternativa que podría ser de utilidad para mejorar el estado fisiológico y bioquímico en el cultivo de tomate.

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