biology and life sciences forum

MDPI

Proceeding Paper

Mineral Interaction in Biofortified Tomatoes (*Lycopersicum esculentum* L.) with Magnesium †

Ana Rita F. Coelho [1,2,*], Inês Carmo Luís [1,2], Ana Coelho Marques [1,2], Cláudia Campos Pessoa [1,2], Diana Daccak [1,2], Maria Manuela Silva [2,3], Manuela Simões [1,2], Fernando H. Reboredo [1,2], Maria F. Pessoa [1,2], Paulo Legoinha [1,2], Carlos Galhano [1,2], Mariana Regato [4], José Regato [4], João Dias [2,4], Nuno Beja [4], Idália Guerreiro [4], José C. Ramalho [2,5], Paula Scotti Campos [2,6], Isabel P. Pais [2,6], José N. Semedo [2,6] and Fernando C. Lidon [1,2]

[1] Earth Sciences Department, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, 2829-516 Caparica, Portugal; idc.rodrigues@campus.fct.unl.pt (I.C.L.); amc.marques@campus.fct.unl.pt (A.C.M.); c.pessoa@campus.fct.unl.pt (C.C.P.); d.daccak@campus.fct.unl.pt (D.D.); mmsr@fct.unl.pt (M.S.); fhr@fct.unl.pt (F.H.R.); mfgp@fct.unl.pt (M.F.P.); pal@fct.unl.pt (P.L.); acag@fct.unl.pt (C.G.); fjl@fct.unl.pt (F.C.L.)
[2] GeoBioTec Research Center, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, 2829-516 Caparica, Portugal; abreusilva.manuela@gmail.com (M.M.S.); joao.dias@ipbeja.pt (J.D.); cochichor@mail.telepac.pt (J.C.R.); paula.scotti@iniav.pt (P.S.C.); isabel.pais@iniav.pt (I.P.P.); jose.semedo@iniav.pt (J.N.S.)
[3] ESEAG-COFAC, Avenida do Campo Grande 376, 1749-024 Lisboa, Portugal
[4] Escola Superior Agrária de Beja, Instituto Politécnico de Beja, 7800-000 Beja, Portugal; mare@ipbeja.pt (M.R.); joseregato@gmail.com (J.R.); nbeja@ipbeja.pt (N.B.); idalia.costa@ipbeja.pt (I.G.)
[5] PlantStress & Biodiversity Lab, Centro de Estudos Florestais (CEF), Instituto Superior Agronomia (ISA), Universidade de Lisboa (ULisboa), Quinta do Marquês, Av. República, 2784-505 Oeiras, Portugal
[6] Instituto Nacional de Investigação Agrária e Veterinária (INIAV), 2784-505 Oeiras, Portugal
* Correspondence: arf.coelho@campus.fct.unl.pt; Tel.: +351-212-948-573
† Presented at the 1st International Electronic Conference on Horticulturae, 16–30 April 2022; Available online: https://sciforum.net/event/IECHo2022.

Citation: Coelho, A.R.F.; Luís, I.C.; Marques, A.C.; Pessoa, C.C.; Daccak, D.; Silva, M.M.; Simões, M.; Reboredo, F.H.; Pessoa, M.F.; Legoinha, P.; et al. Mineral Interaction in Biofortified Tomatoes (*Lycopersicum esculentum* L.) with Magnesium. *Biol. Life Sci. Forum* **2022**, *16*, 16. https://doi.org/10.3390/IECHo2022-12509

Academic Editor: Wilfried Rozhon

Published: 15 April 2022

Abstract: Magnesium is considered an essential nutrient for humans, where about 60% of Mg plays an important role in skeletal development. However, its deficiency can trigger several health pathologies (namely, asthma, Alzheimer's disease, hypertension, and type-2 diabetes). In plants, Mg is especially important, being involved in protein synthesis and correlated with chlorophyll pigments. Its deficiency can compromise photosynthesis and can also lead to shorter roots and necrotic zones in leaves. Mineral deficiency (namely, Mg) in plants can lead to a global problem considering the increase in human population and the need to produce more food that nutritionally meets human needs, being necessary to adopt new technology and approaches. In this context, this study aimed to understand the mineral interactions with Mg biofortification in *Lycopersicum esculentum* (H1534 variety). Biofortification was promoted during the life cycle of the culture throughout six leaf applications with four concentrations (4%, 8%, 12%, and 16%) of MgSO4, equivalent to 702, 1404, 2106, and 2808 g.ha^{-1}. At harvest, 4% $MgSO_4$ treatment showed the highest content of Mg and P and the lowest content of Fe and Zn. Additionally, the highest treatment showed the lowest content of Mg and, on the other hand, the highest content of Fe. In conclusion, despite the synergistic and antagonistic relationships between minerals in the different concentrations of Mg applied, there were no significant changes in total soluble solids content in the fruits.

Keywords: biofortification; H1534 variety; *Lycopersicum esculentum* L.; mineral interaction; natural enrichment with magnesium

1. Introduction

Magnesium is considered an essential nutrient for humans and the fourth most abundant in the body [1], and thus an adequate supply of Mg is important to maintain health [2].

About 60% of Mg is in human bones and plays an important role in skeletal development [3]. Nevertheless, Mg deficiency can trigger several health pathologies, namely, asthma, Alzheimer's disease, hypertension, cardiovascular disease, osteoporosis, and type-2 diabetes mellitus [1,4]. In plants, Mg also plays important roles, namely, in structural and regulatory functions [5]. In fact, Mg has diverse functions and is especially important, being involved in protein synthesis, correlated with chlorophyll pigments [3], is a key element in photosynthesis, and is deeply involved in the phloem loading of sucrose [5]. Its deficiency can compromise plant growth, photosynthesis, and crop productivity, and can also lead to shorter roots and to necrotic zones in leaves [3,5]. Additionally, Mg deficiency in fields can be due to its ionic antagonism with competing cations (H^+, Al^{3+}, Ca^{2+}, K^+, and Na^+) that strongly inhibit Mg^{2+} root uptake [5]. Magnesium is considered a phloem mobile element and is rapidly translocated within the plant to the growing parts, which is why the first symptoms start to appear on older leaves [6]. Mineral deficiency in plants begins to be a global problem considering the increase in the human population and the urge to meet the future worldwide food and nutrient needs [7]. Additionally, with the growth and development of the food industry and agriculture, the ability to produce safe and nutritious food in the future is largely dependent on new technologies and approaches [7]. As such, considering that nutrients are mainly obtained through plants in the human diet [8], agronomic biofortification can be a viable strategy to be implemented with the aim of increasing different mineral contents in the edible part of plants, in particular through foliar fertilization/applications [9]. In this context, since tomato (*Lycopersicum esculentum*) is one of the most popular and consumed horticultural crops globally, and due to the need to improve mineral content in edible crops, this study aimed to understand the mineral interactions (synergistic and antagonistic relationships) in tomatoes of an industrial variety (H1534) biofortified with Mg.

2. Materials and Methods

2.1. Biofortification Itinerary

The experimental tomato-growing field, located in Beja (Alentejo region), South of Portugal (GPS coordinates: 38°01′40″ N; 7°52′20″ W), was used to grow the H1534 variety (*Lycopersicum esculentum* L.). During the agricultural period, from 8 May, 2019 (planting date), to 10 September, 2019 (harvest date), air temperatures reached an average daily of 20.4 and 13.8 °C (with maximum and minimum values varying between 38.9 and 5.7 °C, respectively). Biofortification was promoted during the life cycle of the culture throughout six leaf applications with four concentrations (4%, 8%, 12%, and 16%) of $MgSO_4$, equivalent to 702, 1404, 2106, and 2808 $g.ha^{-1}$. The first foliar application was carried out on 12 July, 2019, and the remaining five foliar applications were performed within a 7- to 11-day interval. Four replicates per concentration were planted, and control plants were not sprayed at any time with $MgSO_4$.

2.2. Mineral Content in Tomatoes

Mineral content was assessed after tomatoes (of similar size) were washed, dried at 60 °C until constant weight, and ground in an agate mortar. After that, the homogenate was divided into four samples ($n = 4$), and an acid digestion procedure was performed with a mixture of HNO3- HClO4 (4:1) according to [10,11]. After filtration, the mineral content of Mg, Ca, Fe, Zn, P, K, and Cu was measured by atomic absorption spectrophotometry, using a model Perkin Elmer AAnalyst 200 (Waltham, MA, USA), and the absorbency was determined with coupled AA WinLab software (version 32).

2.3. Total Soluble Solids

Total soluble solids content was measured in the tomatoes' juice, according to [12].

2.4. Statistical Analysis

Data were statistically analyzed using one-way ANOVA to assess the differences among treatments in the H1534 variety, followed by a Tukey's post-hoc test for mean comparison. A 95% confidence level was adopted for all tests.

3. Results

The mineral content of tomatoes at harvest was assessed in the H1534 variety (Table 1). Mg, Ca, Zn, and Cu did not vary significantly, unlike Fe, P, and K, which varied significantly. The 4% $MgSO_4$ treatment showed the highest content in Mg and P and the lowest content of Fe and Zn. Control showed a higher content of Ca, Zn, K, and Cu compared to the biofortified treatments. Ca, P, K, and Cu showed a lower content in the 12% $MgSO_4$ treatment, and the 8% $MgSO_4$ treatment always presented intermediate values considering the mineral elements analyzed. Additionally, the highest treatment (16% $MgSO_4$) showed the lowest content of Mg and, on the other hand, the highest content of Fe. Relative to control, biofortified tomatoes with 4% and 8% $MgSO_4$ treatments showed an increase in Mg content of 3.5- and 2-6 fold, respectively. In addition, biofortified tomatoes with the 12% $MgSO_4$ treatment showed an increase in Mg content of 2.1%.

Table 1. Mean values ± S.E. ($n = 4$) of Mg, Ca, Fe, and Zn in tomatoes of *Lycopersicum esculentum* (H1534 variety) at harvest. Letters a, b, and c indicate significant differences between treatments (statistical analysis using the single-factor ANOVA test, $p \leq 0.05$). Foliar spray was carried out with four concentrations (4%, 8%, 12%, and 16% $MgSO_4$). Control was not sprayed at any time.

Treatments	**Mg**	**Ca**	**Fe**	**Zn**	**P**	**K**	**Cu**
	mg/100 g						
Control	53.97 a ± 1.08	31.48 a ± 0.16	6.36 b ± 0.13	1.86 a ± 0.47	283 abc ± 9	4616 a ± 44	1.68 a ± 0.24
4% $MgSO_4$	190 a ± 91	30.93 a ± 6.39	5.13 b ± 0.30	0.73 a ± 0.16	315 a ± 10	3509 b ± 89	1.13 a ± 0.02
8% $MgSO_4$	143 a ± 35	31.20 a ± 0.29	6.12 b ± 0.86	1.75 a ± 0.41	270 bc ± 12	3735 b ± 67	1.54 a ± 0.23
12% $MgSO_4$	55.11 a ± 7.43	18.78 a ± 0.91	6.41 b ± 1.05	1.05 a ± 0.41	254 c ± 1	3410 b ± 116	1.08 a ± 0.21
16% $MgSO_4$	49.48 a ± 2.50	19.16 a ± 2.36	10.25 a ± 0.91	1.37 a ± 0.20	297 ab ± 8	3558 b ± 155	1.42 a ± 0.04

Total soluble solids did not vary significantly (Figure 1), yet control showed the lowest content, and 8% $MgSO_4$ treatment showed the highest content compared to the remaining treatments.

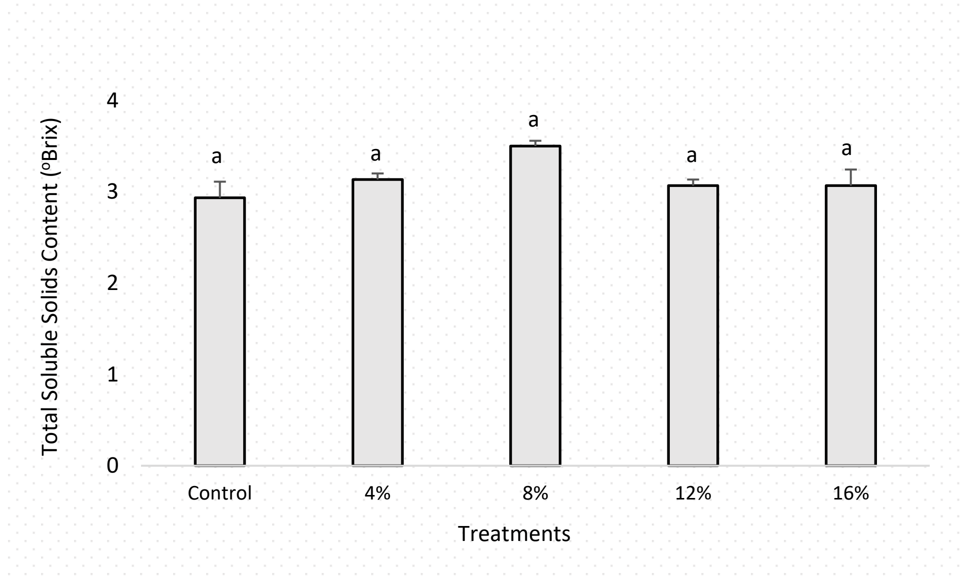

Figure 1. Mean values ± S.E. (n = 4) of total soluble solids (°Brix) in tomatoes of *Lycopersicum esculentum* (H1534 variety) at harvest. Letter a indicates no significant differences between treatments (statistical analysis using the single-factor ANOVA test, $p \leq 0.05$). Foliar spray was carried out with four concentrations (4%, 8%, 12%, and 16% $MgSO_4$). Control was not sprayed at any time.

4. Discussion

Mineral interactions have been proven to be important, mainly regarding indicating deficiencies and toxicity in plants [13]. As such, the mineral content of Mg, Ca, Fe, Zn, P, K, and Cu was assessed in tomatoes at harvest (Table 1). These mineral elements analyzed are considered essential elements for plant growth and development, being supplied by soil or fertilizers [14]. Tomatoes biofortified with $MgSO_4$ showed a higher content of Mg (except in the 6% $MgSO_4$ treatment) regarding control, indicating that biofortification occurred and had a better index with the lower concentration applied (4% $MgSO_4$). Previously, another study carried out with the same variety also showed with 4% $MgSO_4$ treatment the highest Mg content [15]. Nevertheless, the higher content of Mg in the 4% $MgSO_4$ treatment showed a lower Fe content, presenting a tendency of antagonism in the biofortified tomatoes considering that as the Mg content increased, the Fe content decreased. In fact, this antagonistic relationship between Fe and Mg was already verified in the growth and metabolism of another horticultural crop [16]. This type of interaction between ions that have similar chemical properties (in this case, similar size and charge) can lead to competition in the site of absorption, transport, and even function within plant tissues [17]. Additionally, the 16% $MgSO_4$ treatment showed less content of Mg, probably because plants submitted to that concentration started to show signs of toxicity in leaves after six foliar applications. Nevertheless, the 4% $MgSO_4$ treatment that showed the higher Mg content also showed the highest P content regarding the remaining treatments. A previous study carried out by [18] showed evidence of a synergistic mechanism of Mg and P; however, in our study, there is not a clear tendency of that mechanism. Yet, regarding Mg, Ca, and K, there is no tendency of antagonistic interactions, as previously reported by [19] and by [20] (regarding the antagonistic effect of K on Mg content). However, a study carried out by [21] states that the relationship between Mg and K in plant tissues can be antagonistic or synergistic depending, namely, on plant species. It was also reported that the antagonistic relationship of K on Mg is much stronger than Mg on K in both root absorption and in transport within plants, and probably because of that, there is no tendency of an antagonistic effect of Mg on K in our study. In addition, K and Cu showed in the same treatments the highest (in control) and lowest content (12% $MgSO_4$ treatment), also showing lower contents in biofortified treatments. This effect was previously reported by [20], where the higher K content resulted in increased Cu. Additionally, K and Zn also have a synergetic effect [20]; however, our data did not show a clear tendency of that relationship between both mineral elements.

Total soluble solids is considered one of the most relevant parameters in tomatoes [22], with flavors influenced by this content [23]. As such, our data showed higher values in the biofortified treatment and lower values considering the catalog of the variety [24]. Yet, differences in total soluble solids can be due to environmental factors [25].

5. Conclusions

At harvest, tomato (*Lycopersicum esculentum*) of the H1534 variety submitted to a biofortification itinerary with Mg trough foliar spraying showed a higher content in the 4% $MgSO_4$ treatment. Additionally, it was possible to identify an antagonistic effect with Mg and Fe and a tendency for a synergetic relationship with K and Cu. In conclusion, despite the synergistic, antagonistic, and no clear tendency of relationships between the minerals analyzed, there were no significant changes in the total soluble solids content in tomatoes, showing in fact a non-significant increase in biofortified tomatoes with $MgSO_4$.

Supplementary Materials: The presentation material can be downloaded at: https://www.mdpi.com/article/10.3390/IECHo2022-12509/s1.

Author Contributions: Conceptualization, A.R.F.C. and F.C.L.; methodology, F.C.L.; software, A.R.F.C.; formal analysis, A.R.F.C., I.C.L., A.C.M., C.C.P., D.D. and C.G.; investigation, A.R.F.C., D.D., I.C.L., A.C.M. and C.C.P.; resources, M.M.S., M.S., F.H.R., M.F.P., P.L., C.G., M.R., J.R., J.D., N.B., I.G., J.C.R., P.S.C., I.P.P. and J.N.S.; writing—original draft preparation, A.R.F.C.; writing—review and editing, F.C.L.; supervision, F.C.L.; project administration, F.C.L.; funding acquisition, F.C.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work received funding from PDR2020-101-030701 and Fundação para a Ciência e Tecnologia, I.P. (FCT), Portugal, through the research units UIDP/04035/2020 (GeoBioTec) and UIDB/00239/2020 (CEF).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors are grateful to Mariana Regato, José Regato, João Dias, Nuno Beja, and Idália Guerreiro for technical assistance in the production field.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Gröber, U.; Schmidt, J.; Kisters, K. Magnesium in Prevention and Therapy. *Nutrients* **2015**, *7*, 8199–8226. [CrossRef] [PubMed]
2. Schonewille, J.T. Magnesium in dairy cow nutrition: An overview. *Plant Soil* **2013**, *368*, 167–178. [CrossRef]
3. Guo, W.; Nazim, H.; Liang, Z.; Yang, D. Magnesium deficiency in plants: An urgent problem. *Crop. J.* **2016**, *4*, 83–91. [CrossRef]
4. Song, Y.; Ridker, P.M.; Manson, J.E.; Cook, N.R.; Buring, J.E.; Liu, S. Magnesium intake, C-reactive protein, and the prevalence of metabolic syndrome in middle-aged and older U.S. Women. *Diabetes Care* **2005**, *28*, 1438–1444. [CrossRef]
5. Ceylan, Y.; Kutman, U.B.; Mengutay, M.; Cakmack, I. Magnesium applications to growth medium and foliage the starch distribution, increase the grain size and improve the seed germination in wheat. *Plant Soil* **2016**, *406*, 145–156. [CrossRef]
6. Gransee, A.; Führs, H. Magnesium mobility in soils as a challenge for soil and plant analysis, magnesium fertilization and root uptake under adverse growth conditions. *Plant Soil* **2013**, *368*, 5–21. [CrossRef]
7. Clugston, G.A.; Smith, T.E. Global nutrition problems and novel foods. *Asia Pac. J. Clin. Nutr.* **2002**, *11*, S100–S111. [CrossRef]
8. Díaz-Gómez, J.; Twyman, R.M.; Zhu, C.; Farré, G.; Serrano, J.C.; Portero-Otin, M.; Muñoz, P.; Sandmann, G.; Capell, T.; Christou, P. Biofortification of crops with nutrients: Factors affecting utilization and storage. *Curr. Opin. Biotechnol.* **2017**, *44*, 115–123. [CrossRef]
9. Alshaal, T.; El-Ramady, H. Foliar application: From plant nutrition to biofortification. *Environ. Biodivers. Soil Secur.* **2017**, *1*, 71–83. [CrossRef]

10. Carrondo, M.; Reboredo, F.; Ganho, R.; Santos Oliveira, J.F. Heavy metal analysis of sediments in Tejo estuary, Portugal, using a rapid flameless atomic absorption procedure. *Talanta* **1984**, *31*, 561–564. [CrossRef]
11. Reboredo, F.H.S.; Ribeiro, C.A.G. Vertical distribution of Al, Cu, Fe and Zn in soil salt marshes of the Sado estuary, Portugal. *Int. J. Environ. Stud.* **1984**, *23*, 249–253. [CrossRef]
12. Coelho, A.R.F.; Lidon, F.C.; Pessoa, C.C.; Marques, A.C.; Luís, I.C.; Caleiro, J.; Simões, M.; Kullberg, J.; Legoinha, P.; Brito, M.; et al. Can Foliar Pulverization with $CaCl_2$ and $Ca(NO_3)_2$ Trigger Ca Enrichment in *Solanum tuberosum* L. Tubers? *Plants* **2021**, *10*, 245. [CrossRef] [PubMed]
13. Hermans, C.; Chen, J.; Coppens, F.; Inzé, D.; Verbruggen, N. Low magnesium status in plants enhances tolerance to cadmium exposure. *New Phytol.* **2011**, *192*, 428–436. [CrossRef]
14. Uchida, R. Essential nutrients for plant growth: Nutrient functions and deficiency symptoms. *Plant Nutr. Manag. Hawaii's Soils* **2000**, *4*, 31–55.
15. Coelho, A.R.F.; Pessoa, C.C.; Marques, A.C.; Luís, I.C.; Daccak, D.; Silva, M.M.; Simões, M.; Reboredo, F.H.; Pessoa, M.F.; Legoinha, P.; et al. Nutrient Interactions in the Natural Fortification of Tomato with Mg: An Analytical Perspective. *Biol. Life Sci. Forum* **2021**, *4*, 87. [CrossRef]
16. Agarwala, S.C.; Mehrotra, S.C. Iron-magnesium antagonism in growth and metabolism of radish. *Plant Soil* **1984**, *80*, 355–361. [CrossRef]
17. Fageria, N.K. Influence of micronutrients on dry matter yield and interaction with other nutrients in annual crops. *Pesqui. Agropecu. Bras* **2002**, *37*, 1765–1772. [CrossRef]
18. Weih, M.; Liu, H.; Colombi, T.; Keller, T.; Jack, O.; Vallenback, P.; Westerbergh, A. Evidence for magnesium–phosphorus synergism and co-limitation of grain yield in wheat agriculture. *Sci. Rep.* **2021**, *11*, 9012. [CrossRef]
19. Kleiber, T.; Golcz, A.; Krzesinski, W. Effect of magnesium nutrition on onion (*Allium cepa* L.). Part I. Yielding and nutrient status. *Ecol. Chem. Eng.* **2012**, *19*, 97–105. [CrossRef]
20. Armstrong, D.L.; Griffin, K.P.; Danner, M. Better Crops with Plant Food. 1998, Volume LXXXII, No. 3. Available online: http://www.ipni.net/publication/bettercrops.nsf/0/E90E04A957EA624285257980007CD63C/$FILE/BC-1998-3.pdf (accessed on 5 February 2022).
21. Xie, K.; Cakmak, I.; Wang, S.; Zhang, F.; Guo, S. Synergistic and antagonistic interactions between potassium and magnesium in higher plants. *Crop J.* **2021**, *9*, 249–256. [CrossRef]
22. Jarquín-Enríquez, L.; Mercado-Silva, E.M.; Maldonado, J.L.; Lopez-Baltazar, J. Lycopene content and color index of tomatoes are affected by the greenhouse cover. *Sci. Hortic.* **2013**, *155*, 43–48. [CrossRef]
23. Cebrino, F.G.; Ruiz, M.L.; Yuste, M.C.A.; García, M.J.B.; Gómez, D.G. Characterization of traditional tomato varieties grown in organic conditions. *Span J. Agric. Res.* **2011**, *2*, 444–452. [CrossRef]
24. Heinz Company. 2016. Available online: https://www.heinzseed.com/hs_about (accessed on 17 December 2021).
25. Helyes, L.; Pék, Z.; Lugasi, A. Function of the variety technological traits and growing conditions on fruit components of tomato (*Lycopersicon lycopersicum* L. Karsten). *Acta Aliment.* **2008**, *37*, 427–436. [CrossRef]