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2021-01-14
FÖ0435 Product Development and Innovation Systems in Horticulture

EXERCISE 6: MINI-REVIEW

Title

Effects of light on the flavor of greenhouse-produced tomatoes

Introduction

Greenhouse-grown tomatoes have a poor reputation in terms of flavor compared to field-grown tomatoes (Dzakovich et al. 2016). This is problematic for consumers in countries such as Sweden, because field-grown tomatoes are not readily available for purchase; only greenhouse-grown tomatoes are prevalent.

The notion that greenhouses produce tomatoes with inferior flavor poses a bit of a paradox. After all, the promise of controlled environment agriculture is not only greater consistency in output but also the ability to optimize environmental parameters to produce certain desirable qualities. In particular, targeted use of LED lighting allows for eliciting specific flavor profiles in leafy greens. Could the same thing be done for greenhouse-produced tomatoes? More generally, how does light affect flavor development in tomatoes?

This mini-review will survey and summarize the existing research in this area. As light and flavor are both complex topics, basic concepts and definitions will first be briefly introduced.

<u>Light:</u> Light can be parameterized in terms of quality and quantity, in addition to time duration (Ouzounis et al. 2015).

Light quality refers to the distribution of wavelengths (colors) in a light. Historically it was believed that only the 400–700 nm range of the light spectrum (Photosynthetically Active Radiation, PAR) was relevant to photosynthesis, but it is now understood that plants possess photoreceptors sensing Ultraviolet-B, Ultraviolet-A, and Far-Red light. All of these ranges can affect plant development; together, they are known as Photo-Biologically Active Radiation (PBAR) (Table 1).

Table 1. Ranges of Photo-Biologically Active Radiation

Ultraviolet-B (UV-B)	Ultraviolet-A (UV-A)	Photosynthetically Active Radiation (PAR)	Far Red (FR)
280–315 nm	315–400 nm	400–700 nm	700–800 nm

Light quantity refers to the intensity of a light. A common measurement is in terms of cumulative units over time, known as Daily Light Integral (DLI). In a greenhouse environment, light can be natural sunlight and/or supplemental artificial light from various types of lamps (High-Pressure Sodium, LED, etc), each of which have different quality and quantity characteristics. Additionally, light sources can increase air and leaf temperature, affecting transpiration rates and therefore nutrient uptake. Such variation can make the results of experiments difficult to compare (Ouzounis et al. 2015).

Flavor: Flavor involves complex interactions between physiological and biochemical factors (volatiles, sugars, acids) and psychological factors (appearance, mouthfeel, aroma, previous experience, etc.). There is not always a clear correlation between the two (Farneti, B. 2014). Specifically for tomatoes, fruit flavor is affected by a range of factors, sometimes interrelated, from plant genetics and cultivation practices to post-harvest handling (Farneti, B. 2014).

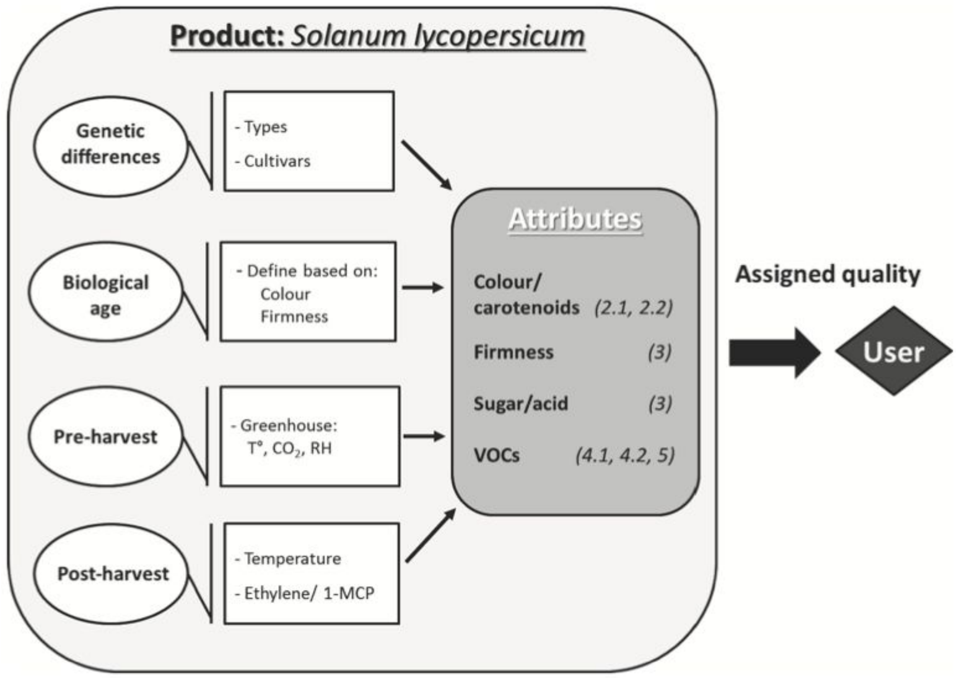


Diagram 1. Factors affecting tomato quality (from Farneti, B. 2014)

Evaluation of flavor, or sensory evaluation, can involve a variety of test methods, both analytic (i.e. objective, quantitative) and hedonic (i.e. affective, qualitative) types. It is critical that the appropriate method be selected for the intended purpose (Lawless, H. T., & Heymann, H. 2013). A 9-point hedonic scale is a standard scale used for assessing consumer liking and preference. Simple ranking is occasionally used as an alternative.

Method

Having established a research topic and problem, the search question was formally defined as follows: “How does light affect flavor development in greenhouse-produced tomatoes?”

To investigate the question, an explicit methodology for conducting a systematic review was followed. The methodology is based on the Search, AppraisaL, Synthesis and Analysis (SALSA) analytical framework (Grant & Booth 2009). The steps are as follows:

Search, Part 1: Search topics were defined corresponding to the concepts of 1) TOMATO, 2) FLAVOR, 3) LIGHT, and 4) GREENHOUSE. The base keywords were augmented with alternate spellings (e.g. “flavor” vs. “flavour”), possible synonyms, and related keywords.

Search, Part 2: Given the initial search queries, possible variations were tested using Clarivate’s Web of Science tool. For example, searching for the Latin name “Solanum lycopersium” instead of “tomato” was tested, but it was determined that while all articles with “Solanum lycopersium” also mentioned “tomato”, the converse was not true. Similarly, searching for wildcards such as “tomato*” and abbreviations such as “UV” and “IR” were not found to be useful. An iterative process was used to refine the queries.

Search, Part 3: The final search procedure was conducted on December 19, 2020 with the following parameters in the Web of Science tool:

- Databases=WOS, CABI
- Search language=English
- Timespan=All years

The search queries and result counts are summarized in Table 2.

Appraisal, Part 1: A number of the search results mention the search keywords but are not relevant to the search question. To identify only the relevant results and filter out the irrelevant results, inclusion and exclusion criteria were developed (Table 3).

Appraisal, Part 2: Where possible, the results were filtered within the Web of Science tool. Specifically, the inclusion criterion I3 (Document type=Article) was applied to exclude results that are not categorized in the databases as articles.

Appraisal, Part 3: At this point, the results were manually subjected to the inclusion and exclusion criteria, based on evaluation of article titles.

Appraisal, Part 4: The results were further refined based on evaluation of article abstracts.

The overall search strategy is depicted in Diagram 2.

Table 2. Search queries and result counts

Set	**Query**	**Results**
#1	TS=(tomato)	183,852
#2	TS=(flavor OR flavour OR taste OR gustatory OR organoleptic)	297,813
#3	TS=(light OR spectrum OR ultraviolet OR infrared)	6,437,503
#4	TS=(greenhouse OR hydroponic)	277,877
#5	#1 AND #2 AND #3 AND #4	64

Table 3. Inclusion and exclusion criteria

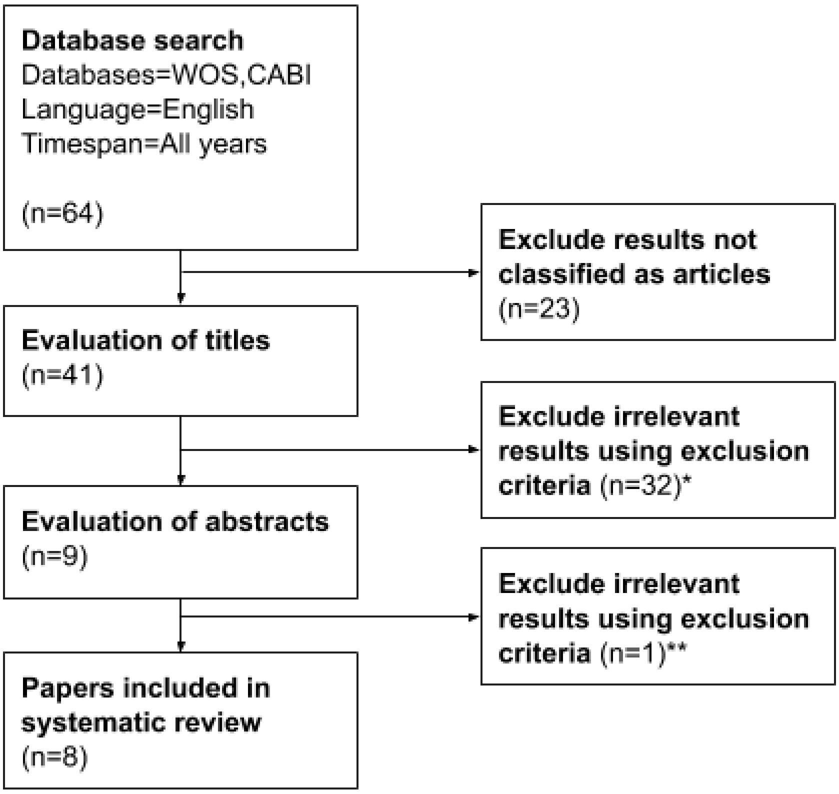
<u>Inclusion criteria</u>

1. The paper is written in English.
2. The paper is published in a scientific journal.
3. The paper is an article (i.e. Document type=Article).

<u>Exclusion criteria</u>

1. The paper is a review.
2. The paper is not relevant to tomato cultivation.
3. The paper is not specific to tomato cultivation.
4. The paper is not relevant to light quality/quantity.
5. The paper is not relevant to light quality/quantity in production (e.g. spectroscopy).
6. The paper is not specific to light quality/quantity.
7. The paper is superseded by subsequent work.

Diagram 2. Flow diagram of search methodology



* See Appendix 2, Articles excluded based on evaluation of titles.
** See Appendix 3, Articles excluded based on evaluation of abstracts.

Results

From the database search, a total of eight articles (Appendix 1) were found to be relevant to the search question. Three of the articles concern UV light, summarized in Table 4. The remaining five articles concern PAR and FR light, summarized in Table 5.

Table 4. Articles concerning the effects of UV light

Article	**Climate**	**Variables Tested**	**Findings**
Dzakovich et al. 2016	Midwestern USA (multiple seasons)	Control, UV-A supplement, UV-A+B supplement	UV-A-supplemented fruits had the highest hedonic ratings for aroma, acidity, and overall approval.
Mariz-Ponte et al. 2019	Portugal	Control, UV-A supplement 1h, UV-A supplement 4h, UV-B supplement 2 min, UV-B supplement 5 min	UV-A supplemented fruits ranked the highest in terms of fruit aroma and flavour.
Papaioannou et al. 2012	Greece	Control, UV-blocking LDPE	Fruit quality characteristics, nutritional value and organoleptic quality were not affected.

Table 5. Articles concerning the effects of PAR and FR light

Article	**Climate**	**Variables Tested**	**Findings**
Dzakovich et al. 2017	Midwestern USA (multiple seasons)	#1: Control, Overhead HPS, Hybrid, Intracanopy LED, Outdoor; #2: Control, RB, R+FR, RB+FR	No significant differences.
Gil et al. 2020	South Korea (simulated off-season)	Overhead R LED 1h, B LED 1h, RB LED 1h, R LED 6h, B LED 6h, RB LED 6h; N, K, Mg: Control, Reduced, Enhanced	Regulating supplemental light (SL) period affected metabolite composition more than varying SL sources.
Kim et al. 2020	Midwestern USA (off-season)	Intracanopy HPS, R LED, R+FR LED	FR plays a key role in fruit quality attributes in tomatoes; Intracanopy R+FR LED significantly improved fruit quality.
Kowalczyk et al. 2012	Poland (off-season)	Overhead HPS, RB LED	Plants supplementary lighted with HPS and LED lamps produced fruit with higher flesh juiciness, sweeter taste and higher overall quality.
Riga et al. 2008	Spain	Control, 70% PAR, 50% PAR; Temperature	Tomato quality is more dependent on temperature than PAR.

<u>Effects of UV light</u>

Light is one of the major differences between greenhouse and field production (Dzakovich et al. 2017). A key difference is that UV radiation is not readily transmissible through greenhouse glass and some greenhouse plastics. In a greenhouse covered by a common low-density polyethylene (PE) film, Papaioannou et al. (2012) reported that UV radiation is reduced to 20.7% and 12.5% for UV-A and UV-B, respectively.

It is known that UV-B radiation, and UV-A radiation to a lesser extent, elicit metabolic and physiological responses in plants, as a reaction to oxidative stress (Dzakovich et al. 2016; Mariz-Ponte et al. 2019). One such response is an increase in the concentration of antioxidant compounds, including ascorbic acid (vitamin C) and phenolics (including flavonoids, which also play a role in UV blocking). Similar responses have been observed with carotenoids in certain tomato cultivars (Dzakovich et al. 2016). Crucially, both flavonoids and carotenoids are synthesized through pathways which also produce several volatile organic compounds (VOCs) that affect tomato flavor (Dzakovich et al. 2016; Mariz-Ponte et al. 2019).

Indeed, both Dzakovich et al. (2016) and Mariz-Ponte et al. (2019) found that supplemental pre-harvest treatments of UV light promote desirable chemical and sensory changes in tomato fruits. UV-A treatments enhanced sensory characteristics (aroma, acidity, and overall approval), firmness (improved shelf life), and concentration of antioxidant compounds (improved nutritional benefits). On a 9-point hedonic scale, UV-A treated tomatoes rated 6.49 ± 0.2, on par with outdoor-grown tomatoes (6.61 ± 0.22), and significantly better than the control with no UV treatment (5.67 ± 0.26) (Dzakovich et al. 2016).

Contrary to expectations, UV-B treatments did not have as much of an effect as UV-A treatments. It is believed that adaptation to UV-B over time reduces the effects of the treatment (Dzakovich et al. 2016). In terms of consumer acceptance, UV-B treated tomatoes actually ranked lower than control and UV-A treated tomatoes, with significant decreases in particular in reddish color, due to increased synthesis of pigments other than the reddish lycopene, (Mariz-Ponte et al. 2019; Papaioannou et al. 2012).

Blocking UV radiation, on the other hand, did not produce differences in tomato quality other than color (Papaioannou et al. 2012). However, there was a significant decrease in the number of insect injured fruit.

Effects of PAR and FR light

In winter months where natural light levels are low, supplemental lighting becomes not only necessary for tomato cultivation but also significantly improves fruit sensory quality (Kim et al. 2020; Kowalczyk et al. 2012). A Polish study of off-season greenhouse tomato production compared overhead High-Pressure Sodium (HPS) lamps with Red-Blue (RB) LED lamps. Both types of supplemental light were found to produce fruit with greater juiciness, sweeter taste, and higher overall quality than the control, i.e. no supplemental light (Kowalczyk et al. 2012). HPS had a greater effect than LED lamps in increasing total sugar content, but this was only significant in one of the two tomato cultivars tested.

A different study of off-season greenhouse tomato production in the midwestern USA compared intracanopy HPS lamps, R LED lamps, and R+FR LED lamps. R+FR LED light was found to perform the best in increasing fruit quality (Kim et al. 2020). Unlike in Kowalczyk et al., in this study HPS produced the least desirable quality attributes. A number of factors, including light position and spectrum, greenhouse location and climate, and tomato cultivars, differed between these studies.

In another study performed in the midwestern USA, overhead HPS light was compared with intracanopy LED light (in different ratios of R, B, and FR), only marginal differences in sensory and chemical characteristics were found (Dzakovich et al. 2017). However, some of the fruit in this study was grown during the summer, rather than in the winter months. The authors concluded that the natural light may have lessened the effects of the supplemental lighting in the greenhouses.

A South Korean study compared the effects of supplemental overhead LED light in different configurations (R, B, RB) and time periods (1 hour, 6 hour) as well as different mineral nutrient recipes (N, K, Mg) (Gil et al. 2020). Crucially, varying the quantity of PAR was found to have a greater effect than the quality (spectrum) of PAR. In particular, tomato fruits subjected to 1 hour of supplemental light exhibited a higher content of amino acids and organic acids, whereas tomato fruits subjected to 6 hours of supplemental light exhibited a higher content of sugars and sugar derivatives. The proportion of sugars versus amino acids and organic acids affect the sweetness and sourness of tomato fruit, respectively.

Finally, a Spanish study investigated the effects of PAR and cumulative air temperature (Riga et al. 2008). Specifically, three levels of PAR (100%, 70%, and 50%) were tested. Temperature was found to have a stronger significant correlation on fruit quality than PAR. Different light quality (spectrum) and sources were not tested in this study.

Discussion

Identifying opportunities for improvement can be seen as a type of innovation search activity; the most successful innovators tend to look beyond the firm's normal knowledge base and domain of expertise (Trott 2017). Indeed, tomato flavor is normally seen through the lens of plant genetics, cultural practices, and post-harvest handling (Farneti, B. 2014), yet as the results of the literature search indicate, environmental factors such as light can be significant as well.

Specifically, supplemental treatments of UV-A and FR light were found to be promising methods to promote desirable chemical and sensory changes in tomato fruits (Dzakovich et al. 2016; Mariz-Ponte et al. 2019; Kim et al. 2020). The effects are still poorly understood; the literature search turned up few relevant studies. Also, the findings were quite specific to the experimental setups in terms of both light configuration and sensory evaluation. For example, Kim et al. (2020) tested intracanopy light, while Kowalczyk et al. (2012) tested overhead light. Dzakovich et al. (2016) assessed 6 sensory attributes using a both 9-point objective scale and a 9-point hedonic scale; in addition, overall approval was assessed using a 9-point hedonic scale. In contrast, Mariz-Ponte et al. (2019) assessed 25 different sensory attributes but used only a 9-point hedonic scale; in addition, consumers performed a hedonic ranking of fruits. Clearly, comparing results across studies is quite problematic.

Crucially, a technical invention is not regarded as a true innovation until it is commercially exploited (Trott 2017). For a greenhouse producer wishing to make use of the research, further R&D activity is needed in order to develop methods to integrate the findings into real-world production processes, at which point using light treatments to improve flavor could become a genuine process innovation within greenhouse tomato production.

Further work may involve in-house R&D and/or external R&D (Trott 2017), potentially partnering with other firms and research institutions with the requisite technical know-how, namely horticultural lighting companies and food testing labs. This is more easily done in some areas than others. For example, in the Netherlands there is an established concentration of interconnected firms and research institutions within greenhouse horticulture production. This so-called industry cluster gives Dutch greenhouse producers distinct competitive advantages (Trott 2017). It is no surprise that today Sweden imports a substantial amount of produce from the Netherlands. For Sweden to become more self-sufficient in terms of food, developing such a horticultural industry cluster could well have greater priority in the context of national innovation.

Process innovations are most commonly associated with cost-reduction efforts on commodity products (Trott 2017). It is certainly true that tomatoes and other fresh produce are not well-differentiated in the supermarket. Here, it would be expected for a tomato with improved flavor to be sold at a premium. The question of how to create market differentiation for flavor-improved tomatoes may fall to the creation of distinctive branding or packaging. Consequently, a process innovation may need to be accompanied by a marketing innovation in order to be successful in the marketplace.

Conclusions

The results suggest that supplemental pre-harvest treatments of UV-A and FR light are potentially useful methods for improving chemical and sensory characteristics in tomato fruits. However, the available research in this area is limited. Additionally, it is difficult to compare results across studies, given the complexities of both light and flavor. Standardization of experimental setups would make it easier to compare findings across studies. Fortunately, both UV-A and FR light sources are low-cost investments, which is advantageous for both further research and for adoption in commercial contexts.

For this research to be successfully commercialized, further work is needed, both in terms of developing the changes in real-world production processes and also in terms of creating differentiation in the marketplace.

Ultimately, it is not inconceivable that someday, greenhouse-produced tomatoes will actually be superior in flavor—not inferior—to field-grown tomatoes.

References

Farneti, B. (2014). Tomato quality: from the field to the consumer : interactions between genotype, cultivation and postharvest conditions. (phd). Wageningen University. Available at: https://library.wur.nl/WebQuery/wurpubs/456555 [2020-12-19]

Grant, M.J. & Booth, A. (2009). A typology of reviews: an analysis of 14 review types and associated methodologies. *Health Information & Libraries Journal*, 26 (2), 91–108. https://doi.org/10.1111/j.1471-1842.2009.00848.x

Lawless, H. T., & Heymann, H. (2013). *Sensory evaluation of food: principles and practices.* Springer Science & Business Media.

Ouzounis, T., Rosenqvist, E. & Ottosen, C.-O. (2015). Spectral Effects of Artificial Light on Plant Physiology and Secondary Metabolism: A Review. *Hortscience*, 50 (8), 1128–1135. https://doi.org/10.21273/HORTSCI.50.8.1128

Trott, P. (2017). *Innovation management and new product development*. 6th Edition. Harlow, England: Pearson.

Appendix 1: Articles included in the results

Article	**Aspects Studied**
Dzakovich, M.P., Ferruzzi, M.G. & Mitchell, C.A. (2016). Manipulating Sensory and Phytochemical Profiles of Greenhouse Tomatoes Using Environmentally Relevant Doses of Ultraviolet Radiation. *Journal of Agricultural and Food Chemistry*, vol. 64 (36), pp. 6801–6808	UV (supplemental)
Dzakovich, M.P., Gomez, C., Ferruzzi, M.G. & Mitchell, C.A. (2017). Chemical and Sensory Properties of Greenhouse Tomatoes Remain Unchanged in Response to Red, Blue, and Far Red Supplemental Light from Light-emitting Diodes. *Hortscience*, vol. 52 (12), pp. 1734-+	PAR + FR (supplemental)
Gil, H.J., Kim, Y.X., Sung, J., Jung, E.S., Singh, D., Lee, Y., Lee, D., Lee, C.H. & Lee, S. (2020). Metabolomic insights of the tomato fruits (Solanum lycopersicum L.) cultivated under different supplemental LED lighting and mineral nutrient conditions. *Horticulture Environment and Biotechnology*, vol. 61 (2), pp. 415–427	PAR (supplemental) vs. Nutrients, Off-season (simulated)
Kim, H.-J., Yang, T., Choi, S., Wang, Y.-J., Lin, M.-Y. & Liceaga, A.M. (2020). Supplemental intracanopy far-red radiation to red LED light improves fruit quality attributes of greenhouse tomatoes. *Scientia Horticulturae*, vol. 261, p. 108985	PAR + FR (supplemental), Off-season
Kowalczyk, K., Gajc-Wolska, J., Metera, A., Mazur, K., Radzanowska, J. & Szatkowski, M. (2012). Effect of supplementary lighting on the quality of tomato fruit (Solanum lycopersicum L.) in autumn-winter cultivation. In: Hemming, S. & Heuvelink, E. (eds.) *Acta Horticulturae*. pp. 395–402.	PAR (supplemental), Off-season
Mariz-Ponte, N., Martins, S., Goncalves, A., Correia, C.M., Ribeiro, C., Dias, M.C. & Santos, C. (2019). The potential use of the UV-A and UV-B to improve tomato quality and preference for consumers. *Scientia Horticulturae*, vol. 246, pp. 777–784	UV (supplemental)
Papaioannou, C., Katsoulas, N., Maletsika, P., Siomos, A. & Kittas, C. (2012). Effects of a UV-absorbing greenhouse covering film on tomato yield and quality. *Spanish Journal of Agricultural Research*, vol. 10 (4), pp. 959–966	UV (blocking)
Riga, P., Anza, M. & Garbisu, C. (2008). Tomato quality is more dependent on temperature than on photosynthetically active radiation. *Journal of the Science of Food and Agriculture*, vol. 88 (1), pp. 158–166	PAR (shading) vs. Temperature

Appendix 2: Articles excluded based on evaluation of titles

Article	Notes
Ando, A., Nakano, A., Kaneko, S., Sakaguchi-Yokoyama, R., Higashide, T., Hatanaka, M. & Kimura, S. (2015). Characteristics of **taste components and fruit yields** of Dutch and Japanese tomato cultivars. *Bulletin of the National Institute of Vegetable and Tea Science*, (14), pp. 31–38	E4 (Not relevant to light)
Borghi, S. (2004). Table tomato special. *Colture Protette*, vol. 33 (8), pp. 15–42	E4 (Not relevant to light)
Clement, A., Dorais, M. & Vernon, M. (2008). Nondestructive Measurement of Fresh Tomato Lycopene Content and Other Physicochemical Characteristics Using **Visible-NIR Spectroscopy**. *Journal of Agricultural and Food Chemistry*, vol. 56 (21), pp. 9813–9818	E5 (Not relevant to light in production)
Deborde, C., Maucourt, M., Baldet, P., Bernillon, S., Biais, B., Talon, G., Ferrand, C., Jacob, D., Ferry-Dumazet, H., de Daruvar, A., Rolin, D. & Moing, A. (2009). **Proton NMR quantitative profiling** for quality assessment of greenhouse-grown tomato fruit. *Metabolomics*, vol. 5 (2), pp. 183–198	E5 (Not relevant to light in production)
Deegan, K.C., Koivisto, L., Nakkila, J., Hyvonen, L. & Tuorila, H. (2010). Application of a **sorting procedure** to greenhouse-grown cucumbers and tomatoes. *Lwt-Food Science and Technology*, vol. 43 (3), pp. 393–400	E4 (Not relevant to light)
Dorais, M., Papadopoulos, A.P. & Gosselin, A. (2001a). Greenhouse tomato fruit quality. *Horticultural Reviews*. pp. 239–319.	E1 (Review)
Dorais, M., Papadopoulos, A.P. & Gosselin, A. (2001b). Influence of **electric conductivity** management on greenhouse tomato yield and fruit quality. *Agronomie*, vol. 21 (4), pp. 367–383	E4 (Not relevant to light)
Forney, C.F., LeBlanc, D.I., Vigneault, C., Toussaint, V., Bourgeois, G., Clement, A. & Bezanson, G. (2018). The interaction of **storage temperature and duration** on aroma volatiles in tomato fruit. In: Artes-Hernandez, F., Gomez, P.A., Aguayo, E., & Artes, F. (eds.) *Acta Horticulturae*. pp. 343–350.	E4 (Not relevant to light)
Gajewski, M., Mazur, K., Radzanowska, J., Kowalczyk, K., Marcinkowska, M., Ryl, K. & Kalota, K. (2014). Sensory Quality of “Cherry” Tomatoes in Relation to **1-MCP Treatment and Storage Duration**. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, vol. 42 (1), pp. 30–35	E4 (Not relevant to light)
Gruda, N. (2005). Impact of environmental factors on product quality of greenhouse vegetables for fresh consumption. *Critical Reviews in Plant Sciences*, vol. 24 (3), pp. 227–247	E1 (Review); E3 (Not specific to tomato)
Helyes, L., Brandt, S. & Reti, K. (2003). Appreciation and analysis of **lycopene content** of tomato. In: Tijskens, L.M.M. & Vollebregt, H.M. (eds.) *Proceedings of the International Conference on Quality in Chains, Vols 1 and 2: An Integrated Viw on Fruit and Vegetable Quality*. pp. 531–537.	E4 (Not relevant to light)
Higashide, T., Yasuba, K., Suzuki, K., Nakano, A. & Ohmori, H. (2012). Yield of Japanese Tomato Cultivars Has Been Hampered by a **Breeding** Focus on Flavor. *Hortscience*, vol. 47 (10), pp. 1408–1411	E4 (Not relevant to light)
Hirai, T., Fukukawa, G., Kakuta, H., Fukuda, N. & Ezura, H. (2010). Production of **Recombinant Miraculin** Using Transgenic Tomatoes in a Closed Cultivation System. *Journal of Agricultural and Food Chemistry*, vol. 58 (10), pp. 6096–6101	E4 (Not relevant to light)
Ho, L.C. (1995). **Carbon** partitioning and metabolism in relation to plant growth and fruit production in tomato. In: FernandezMunoz, R., Cuartero, J., & GomezGuillamon, M.L. (eds.) *First International Symposium on Solanacea for Fresh Market*. pp. 396–409.	E4 (Not relevant to light)

Hwang, C.Y., Choi, K.M. & Park, J.S. (1987). Studies on bionomics of the **Oriental tobacco budworm**, Heliothis assulta Guenee. *Research Reports of the Rural Development Administration, Plant Environment, Mycology & Farm Products Utilization*, Korea Republic, vol. 29 (2), pp. 95–113	E4 (Not relevant to light)
Jose Iglesias, M., Garcia Lopez, J., Collados Lujan, J.F., Lopez Ortiz, F., Bojorquez Pereznieto, H., Toresano, F. & Camacho, F. (2014). Effect of genetic and phenotypic factors on the composition of commercial marmande type tomatoes studied through **HRMAS NMR spectroscopy**. *Food Chemistry*, vol. 142, pp. 1–11	E5 (Not relevant to light in production)
Jose Iglesias, M., Garcia-Lopez, J., Fernando Collados-Lujan, J., Lopez-Ortiz, F., Diaz, M., Toresano, F. & Camacho, F. (2015). Differential response to **environmental and nutritional factors** of high-quality tomato varieties. *Food Chemistry*, vol. 176, pp. 278–287	E6 (Not specific to light)
Karaagac, O. (2020). Hybrid Cucurbita Rootstocks Improve Root Architecture, Yield, Quality, and Antioxidant Defense Systems of **Cucumber** (Cucumis sativus) Under Low Temperature Conditions. *International Journal of Agriculture and Biology*, vol. 23 (3), pp. 613–622	E2 (Not relevant to tomato)
Kudryavtseva, G.A., Tropina, L.P., Lazareva, T.A. & Petruseva, A.F. (1981). **Promising form of tomato** for western Siberia. *Kartofel' i Ovoshchi*, (8), pp. 31–32	E4 (Not relevant to light)
Kwon, M.C., Kim, Y.X., Lee, S., Jung, E.S., Singh, D., Sung, J. & Lee, C.H. (2019). Comparative Metabolomics Unravel the Effect of **Magnesium** Oversupply on Tomato Fruit Quality and Associated Plant Metabolism. *Metabolites*, vol. 9 (10), p. 231	E4 (Not relevant to light)
Leiva-Ampuero, A., Agurto, M., Tomas Matus, J., Hoppe, G., Huidobro, C., Inostroza-Blancheteau, C., Reyes-Diaz, M., Stange, C., Canessa, P. & Vega, A. (2020). **Salinity** impairs photosynthetic capacity and enhances carotenoid-related gene expression and biosynthesis in tomato (Solanum lycopersicum L. cv. Micro-Tom). *Peerj*, vol. 8, p. e9742	E4 (Not relevant to light)
Mayer, F., Takeoka, G.R., Buttery, R.G., Whitehand, L.C., Naim, M. & Rabinowitch, H.D. (2008). Studies on the **aroma** of five fresh tomato cultivars and the precursors of cis- and trans-4,5-epoxy-(E)-2-decenals and methional. *Journal of Agricultural and Food Chemistry*, vol. 56 (10), pp. 3749–3757	E4 (Not relevant to light)
Moles, T.M., Francisco, R. de B., Mariotti, L., Pompeiano, A., Lupini, A., Incrocci, L., Carmassi, G., Scartazza, A., Pistelli, L., Guglielminetti, L., Pardossi, A., Sunseri, F., Hoertensteiner, S. & Santelia, D. (2019). **Salinity** in Autumn-Winter Season and Fruit Quality of Tomato Landraces. *Frontiers in Plant Science*, vol. 10, p. 1078	E4 (Not relevant to light)
Mozafarian, M., Ismail, N.S.B. & Kappel, N. (2020). Rootstock Effects on Yield and Some Consumer Important Fruit Quality Parameters of **Eggplant** cv. “Madonna” under Protected Cultivation. *Agronomy-Basel*, vol. 10 (9), p. 1442	E2 (Not relevant to tomato)
Ouzounis, T., Rosenqvist, E. & Ottosen, C.-O. (2015). Spectral Effects of Artificial Light on Plant Physiology and Secondary Metabolism: **A Review**. *Hortscience*, vol. 50 (8), pp. 1128–1135	E1 (Review); E3 (Not specific to tomato)
Ramin, A.A. (2006). Improving postharvest quality of glasshouse tomatoes treated with **1-MCP** at ripeness stage. *American-Eurasian Journal of Agricultural and Environmental Science*, vol. 1 (2), pp. 149–155	E4 (Not relevant to light)
Sanchez-Gonzalez, M.J., Sanchez-Guerrero, M.C., Medrano, E., Porras, M.E., Baeza, E.J. & Lorenzo, P. (2016). **Carbon dioxide enrichment**: a technique to mitigate the negative effects of **salinity** on the productivity of high value tomatoes. *Spanish Journal of Agricultural Research*, vol. 14 (2), p. e0903	E4 (Not relevant to light)
TRIEBELS, H. (1927). Tbe control of **leaf mould** of Tomatoes. *Gartenwelt*, vol. 31 (18), pp. 268–270	E4 (Not relevant to light)

Verheul, M.J., Slimestad, R. & Tjostheim, I.H. (2015). From Producer to Consumer: Greenhouse Tomato Quality As Affected by **Variety, Maturity Stage at Harvest, Transport Conditions, and Supermarket Storage**. *Journal of Agricultural and Food Chemistry*, vol. 63 (20), pp. 5026–5034	E4 (Not relevant to light)
Vieira, J.L.M. & Hanada, R.E. (2019). Quality of tomato (Solanum lycopersicum L.) due to **grafting** in Solanaceae of different species. *Journal of Agricultural Science (Toronto)*, vol. 11 (3), pp. 188–196	E4 (Not relevant to light)
Walters, K.J., Behe, B.K., Currey, C.J. & Lopez, R.G. (2020). Historical, Current, and Future Perspectives for Controlled Environment Hydroponic Food Crop Production in the United States. *Hortscience*, vol. 55 (6), pp. 758–767	E1 (Review); E3 (Not specific to tomato); E6 (Not specific to light)
Zatyko, L. (2006). Selection of **paprika** in ancient times and today. (Paldi, E., ed.) *Acta Agronomica Hungarica*, vol. 54 (2), pp. 167–178	E2 (Not relevant to tomato); E4 (Not relevant to light)

Appendix 3. Articles excluded based on evaluation of abstracts

Article	**Notes**
Dzakoyich, M.P., Gomez, C. & Mitchell, C.A. (2015). Tomatoes Grown with Light-emitting Diodes or High-pressure Sodium Supplemental Lights have Similar Fruit-quality Attributes. *Hortscience*, vol. 50 (10), pp. 1498–1502	E7 (Superseded)