Proceedings 8th International Food Operations & Processing Simulation Workshop (FoodOPS), 010
19th International Multidisciplinary Modeling & Simulation Multiconference

2724-0355 © 2022 The Authors.
doi: 10.46354/i3m.2022.foodops.010

Performance assessment, through CFD simulation, of an ultraviolet reactor for the processing of fruit juices

Roberto Montanari[1], Andrea Volpi[1], Federico Solari[1,*], Natalya Lysova[1]

[1]University of Parma - Department of Engineering and Architecture, Viale delle Scienze 181/A, Parma, 43124, Italy

[*]Corresponding author. Email address: federico.solari@unipr.it

Abstract

Computational Fluid Dynamics (CFD) was used to predict the performance of an ultraviolet reactor employed for the pasteurization of orange and pineapple fruit juices. The rheological characteristics of the juices were measured, as well as their absorption coefficient at 254 nm. A numerical simulation approach was used to compute both the flow field for 4 different flow rates (20, 40, 60 and 100 l/h) and the radiation field, generated using a commercial lamp. The possible trajectories and the correlated residence times of the particles and microorganisms flowing through the reactor were calculated using a discrete phase model (DPM). The dose absorbed was calculated by integrating over time the light intensity along each trajectory, and the performances were evaluated in terms of dose distribution (minimum, maximum and average dose). The approach adopted allowed also for evaluating the uniformity of the process and optimizing it, to avoid insufficient doses on some trajectories or excessive doses on others, with a consequent risk of re-contamination or formation of unwanted by-products, respectively. This represents a big advantage compared to most of the studies present in the literature, where the performances are assessed through experimental approaches, which do not allow for evaluating the uniformity of the treatment.

Keywords: ultraviolet radiation, fruit juice, CFD simulation, parametric study, pasteurization

1. Introduction and state of the art

In recent years, consumer demand has increasingly shifted toward products with organoleptic and sensory characteristics as similar as possible to those of fresh products. Consequently, the interest in non-thermal treatments has grown more and more, as evidenced by the growing number of scientific publications on the subject (Abrahamsen and Narvhus, 2022; Basak and Chakraborty, 2022; Basak et al., 2022; Umair et al., 2022; Wang and Xu, 2022; Kontopodi et al., 2022). With regard to fruit juices, ultraviolet (UV) radiation is one of the most promising treatments, since it allows to obtain microbiologically safe products with less undesirable alterations to the food than traditional heat treatments.

The UV pasteurization process, achieved by working in the wavelength range that varies between 100 nm and 400 nm and, in particular, in the UV-C region (100 nm – 280 nm), inactivates bacteria, viruses, molds, and other microorganisms by altering the genetic material in their cells. Within the UV-C region, the most effective wavelength, in terms of germicidal effect, is 254 nm, as this is the wavelength at which photons are best absorbed by the DNA of microorganisms (Koutchma, 2009).

The main issue in the application of UV radiation for pasteurization of opaque fluids in general, and fruit juices in particular, is related to the poor penetration ability of light within the fluid, due to the presence of solutes and/or suspended elements. For this reason, the performances of UV reactors must be evaluated on a case-by-case basis, depending on the rheological characteristics and, especially, on the absorption coefficient of the fluid at 254 nm.

In recent years many studies have been conducted to evaluate the performance of different reactor geometries on several types of juice. Mansor et al. (2014) have investigated the efficacy of UV-C treatment with the Dean Vortex technology on pineapple juice. They have found that a 5-log10 reduction in *Salmonella typhimurium* can be obtained with a dosage of 13.75 mJ/cm². The same technology has been tested by Müller et al., (2011), who have observed that 5-log10 and 6-log10 reductions could be achieved by inactivating *Lactobacillus plantarum* BFE 5092 and *Escherichia coli* DH5α in naturally cloudy apple juice with doses of 1.9 and 7.7 kJ/L, respectively. Shamsudin et al., (2012) have treated filtered pineapple juice with a CiderSure 3500-B device, equipped with eight low-pressure lamps. They have applied a dose of 21.52 mJ/cm² on a thin film of juice, having a thickness ranging between 0.21 and 0.48 mm. They have found that a 1.91-log10 reduction and a 1.4-log10 reduction could be observed in the total plate count and in the yeast and mold count, respectively. Keyser et al. (2008) have tested 10 stainless steel reactors in series, each consisting of a corrugated spiral tube, equipped with a 30 W UV-C output germicidal lamp. They have achieved a 3.31-log10 reduction in aerobic plate count (APC) and a 4.48-log10 reduction in yeast and mold count (YM) after supplying a dose of 1377 J/L to guava-and-pineapple juice. In the case of orange juice, characterized by a higher absorption coefficient, a reduction of less than 1(0.3)-log10 has been obtained in both APC and YM counts, even with a dose of 1607 J/L. Tran and Farid (2004) have processed orange juice with a reactor consisting of a 50-mm diameter and 450-mm-long glass tube, fixed vertically, equipped with a 6 W UV-C lamp enclosed in a quartz tube. In this system, the product flows by gravity along the glass tube, generating a thin film with a thickness between 0.21 and 0.48 mm. The researchers have achieved a 3-log10 reduction in aerobic plate count (APC) and a 2.4-log10 reduction in yeast and mold count (YM) after a dose of 123 mJ/cm².

In all the studies cited, the dose delivered by the reactor has been evaluated either in terms of average dose, calculated as the product of UV-C power per unit area and average residence time, expressed in mJ/cm², or in terms of total installed UV-C power per unit flow rate, expressed in J/l. These approaches, while providing important information about the effectiveness of the treatment, do not provide any insight into its uniformity. Indeed, for the treatment to be effective, it is necessary to guarantee the minimum dose for obtaining the desired logarithmic reductions in the target microorganism, in the whole volume of fluid, to avoid the risk of re-contamination. On the other hand, excessive exposure to radiation could cause unwanted alterations in the product (ascorbic acid losses, decrease in carotenoids, phenolic acids, antioxidant capacity and formation of furan) (Pala and Toklucu, 2013; Shamsudin et al., 2012; Shah et al., 2015). In light of this, it is clear how essential it is, in the design phase, to size a machine able to guarantee a uniform treatment.

In the case of UV radiation, the uniformity of the treatment is affected by the absorption coefficient of the product at the sterilizing wavelength, the fluid thickness, and the concentration of suspended particles, as well as by the geometry of the reactor, the product flow rate and turbulence. To this end, Computational Fluid Dynamics simulation could be very useful for the optimization of machine geometric parameters to achieve the desired performance. To date, however, only a few studies have used a simulation approach to investigate and optimize a UV reactor for fruit juice treatment (Unluturk et al., 2004, Buhler et al., 2019, Sultan et al., 2021).

In this study, we use a simulation approach to investigate the performance of a stainless steel reactor, employed for the treatment of orange and pineapple juices. The reactor consists of a pipe with a length of 850 mm and an internal diameter of 31 mm, equipped with an amalgam germicidal lamp characterized by UV-C output of 35 W at 254 nm. The lamp is enclosed in a quartz tube having an external diameter of 28 mm. First, for both fluids, the physical properties of interest, such as the absorption coefficient at 254 nm, the dynamic viscosity, and the density were measured. Then, a parametric study was carried out, considering four different flow rates (20 l/h, 40 l/h, 60l/h and 100 l/h), to evaluate the performance of the reactor, in terms of the radiation dose absorbed by the two juices, as the flow rate varied. For each configuration, both the flow field and the radiation field were computed. The dose distribution was calculated by tracking a sufficient number of flow patterns and then integrating the UV intensity over time along each trajectory.

The results obtained show how the performance of the simulated device, characterized by a simple structure without any hygienic criticalities and low construction costs, is strongly influenced by both the characteristics of the juice and the flow rate. Finally, our study demonstrates how CFD simulation allows for deeper understanding of the process and, as a result, for greater control over the process itself.

2. Materials and methods

2.1. Physical characterization of fruit juices

The dynamic viscosities of the juices were measured using a rotational coaxial cylinder viscometer, consisting of two coaxial cylinders: the external one rotates at a constant speed, while the other is held in place. The fluid is placed between the gaps of the two cylinders while a specific instrument (Brookfield Engineering RST Controlled Stress Rheometer) collects the data.

Absorption coefficients were evaluated at the sterilizing wavelength of 254 nm through spectrophotometry (Aquamate - Thermo Electron Corporation).

2.2. Ultraviolet pasteurizer

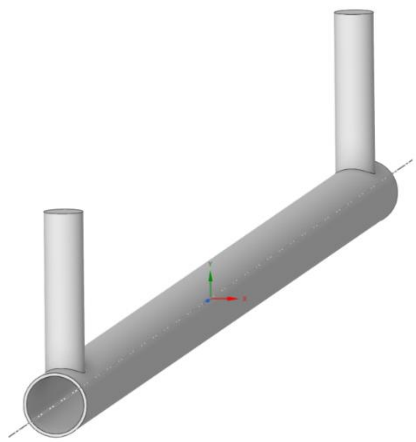

Figure 1. Geometry of the UV reactor.

The reactor consists of a stainless steel pipe, with a length of 850 mm and an internal diameter of 31 mm. An amalgam UV-C lamp, having a total power of 110 W (35 W at 254 nm), is positioned in the inner chamber, co-axially to the steel tube. The lamp is fitted inside a quartz sleeve, to avoid direct contact with the juice. The inlet and outlet ducts of the reactor are arranged in a U-shape layout. The geometry is presented in Figure 1.

2.3. CFD simulation

Ansys® Release 2021 R2 was used for the CFD modeling. For all the configurations, the Reynolds number resulted much lower than 2100, so the simulations were performed in laminar flow regime. The inlet boundary condition was defined by setting the fluid velocity, while a relative pressure of 0 Pa was specified at the outlet section. No-slip condition was set on all reactor surfaces. Radiation intensity per unit area, calculated as the ratio between the lamp power at the the wavelength of 254 nm and the surface area of the sleeve, was specified for the quartz surface. The UV radiation field was computed using Discrete Ordinates (DO) radiation model. 500 fluid trajectories, starting from the inlet section, were calculated using the discrete phase model (DPM), based on a Lagrangian approach. Finally, the UV dose distribution was computed by integrating the light intensity along each trajectory over time.

3. Results and Discussion

The results of the physical characterization of the juices are reported In Table 1.

Table 1. Physical properties of orange juice and pineapple juice

Type of juice	Dynamic viscosity [Pa s]	Absorption coefficient [cm^{-1}]
Orange	0.012	50
Pineapple	0.014	75

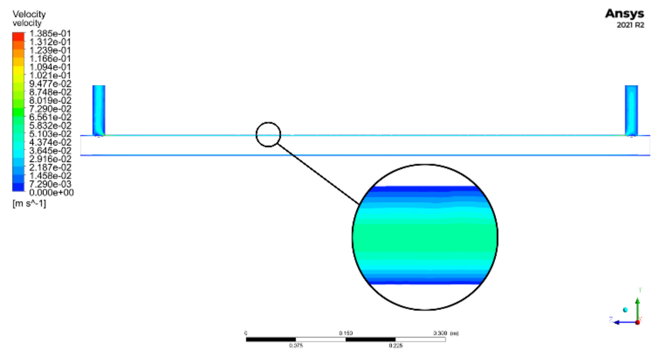

Figure 2. Distribution of velocity on a longitudinal section plane.

The velocity distribution on a longitudinal section plane, in the case of orange juice and a flow rate of 40 l/h, is presented in Figure 2.

As stated in the Introduction, the radiation field was calculated inside the whole fluid volume, taking into account the absorption coefficients of the two juices. A comparison of the radiation field in the case of orange juice and pineapple juice is shown in Figure 3.

It is evident that in the case of pineapple juice, due to its higher absorption coefficient, the penetration of light radiation is much lower compared to orange juice. In both cases, it is clear that it would be appropriate to reduce the thickness of the fluid film. In the device considered, however, the thickness of the fluid was not reduced further to avoid very tight machining tolerances and, consequently, higher construction costs.

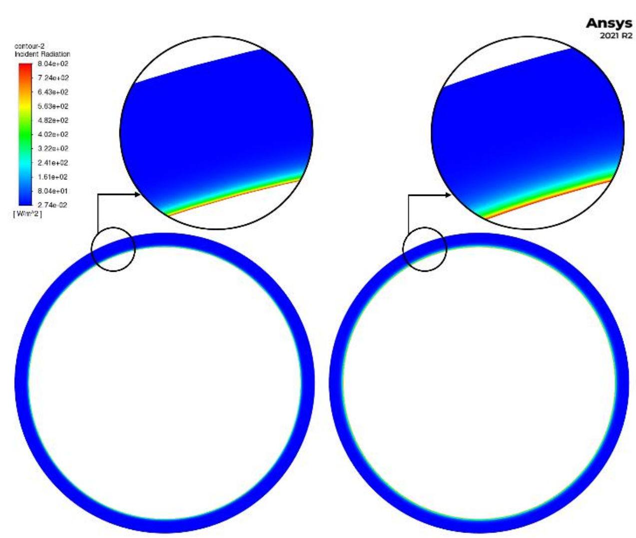

Figure 3. Radiation fields in the case of pineapple (left) and orange (right) juices

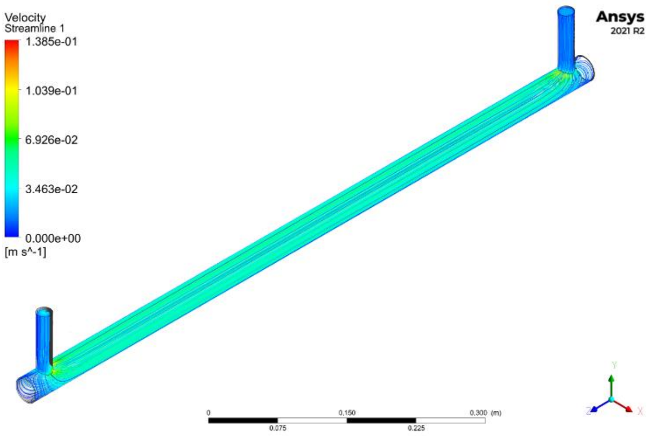

Figure 4. Streamlines of velocity, sampled from 500 seed points.

Based on the fluid-dynamic results, in particular the velocity field, the trajectories of 500 fluid particles were calculated. The resulting velocity streamlines, in the case of orange juice at a flow rate of 40 l/h, are presented in Figure 4.

After computing both the trajectories and the radiation field, the UV dose absorbed by each particle was calculated by integrating the light intensity along each trajectory over time. Figure 5 shows the dose distributions obtained for orange juice and pineapple juice with a flow rate of 20 l/h. It can be seen that the distribution obtained for orange juice is shifted toward higher dose values. This is because in orange juice the UV light can penetrate deeper, thanks to a lower absorption coefficient. It can also be seen that, for both juices, the dose distribution is characterized by a rather high variability. This occurs because, since the flow inside the reactor is laminar, there is limited stirring and the trajectories of the particles are parallel to the lamp (Figure 4). As a result, the fluid layers closer to the lamp absorb high radiation doses, while layers that are more distant from the lamp absorb lower doses. It would be desirable to insert elements that would increase the mixing inside the reactor, or to use a spirally corrugated tube to impart helical motion to the fluid. All the changes introduced into the machine, however, must be evaluated to ensure the hygiene and cleanability of the reactor. The trends in average, minimum, and maximum dose for the two juices, as the flow rate varies, are shown in Figure 6.

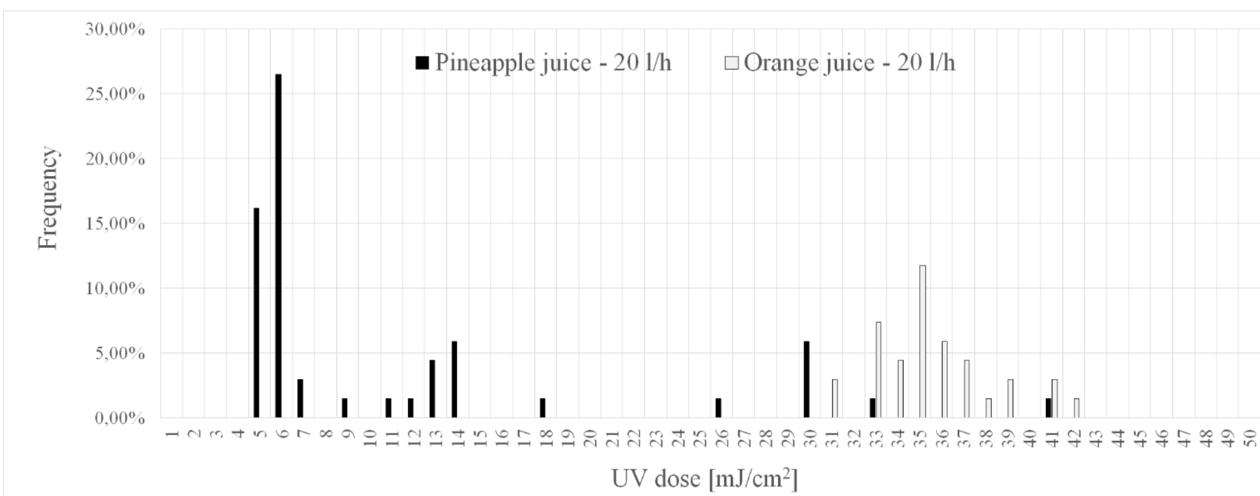

Figure 5. Distribution of the radiation dose with a flow rate of 20 l/h.

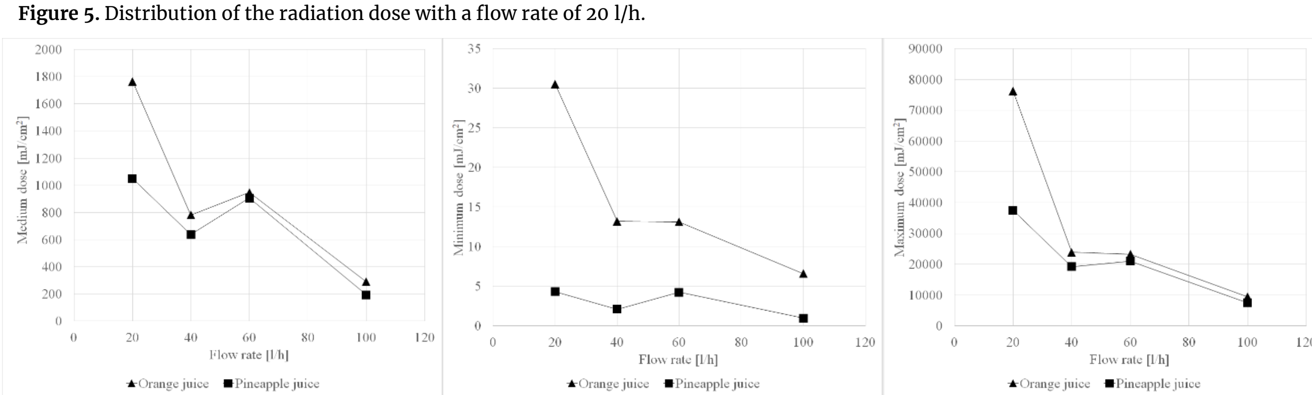

Figure 6. Trends in medium, minimum and maximum doses at different flow rate values.

Looking at the graphs, it is evident how the system performance tends to decrease as the flow rate increases since, for the same radiation field, the residence time decreases. The increase in performance that occurs between 40 and 60 l/h can be explained by an increase in fluid turbulence, which enhances the uniformity of the treatment and, consequently, compensates for the reduction in residence time. This result confirms what has been achieved by Mansor et al. (2014).

Looking at the medium doses, it can be seen that the reactor, for both juices, can provide dosages comparable with those found in the literature. However, especially in the case of pineapple juice, it can be seen that the minimum doses are very low, ranging from 5 to 1 mJ/cm^2, meaning that a portion of the product may not reach the required treatment level. In addition, the results also show that, for both juices, very high maximum doses are reached, which can result in the formation of undesirable by-products.

To increase the minimum dose guaranteed by the process, it would be possible to consider placing more reactors in series. On the other hand, this would also cause an increase in the maximum dose. The optimal solution would be to modify the geometry of the reactor, aiming to increase the uniformity of the treatment. Possible approaches could be, for example, a reduction in fluid thickness or the introduction of elements that would increase the turbulence of the fluid without increasing its flow rate.

4. Conclusions

In this study, the application of CFD simulation for the evaluation of the performance of a UV reactor for fruit juices was investigated. The study demonstrates that the method proposed has several advantages over an experimental approach:

- It allows for predicting how the performance of the reactor may vary, according to the physical characteristics of the fluid treated;
- It makes it possible to evaluate the uniformity of the treatment, allowing to estimate if there are fluid regions subjected to excessively low or high radiation doses;
- It allows for assessing how the changes in the geometry of the reactor could affect its performance.

Future research activities will have to focus on the validation of the simulation model, and on the evaluation of geometric modifications aimed at enhancing the uniformity of the treatment and decreasing the influence of the absorption coefficient of the fluid treated on the performance of the reactor.

References

Abrahamsen, R. K., & Narvhus, J. A. (2022). Can ultrasound treatment replace conventional high temperature short time pasteurization of milk? A critical review. International Dairy Journal, 131, 105375. doi:10.1016/j.idairyj.2022.105375

Basak, S., & Chakraborty, S. (2022). The potential of nonthermal techniques to achieve enzyme inactivation in fruit products. Trends in Food Science & Technology, 123, 114–129. doi:10.1016/j.tifs.2022.03.008

Basak, S., Mahale, S., & Chakraborty, S. (2022). Changes in quality attributes of pulsed light and thermally treated mixed fruit beverages during refrigerated storage (4 °C) condition. Innovative Food Science & Emerging Technologies, 78, 103025. doi:10.1016/j.ifset.2022.103025

Buhler, S., Solari, F., Gasparini, A., Montanari, R., Sforza, S., Tedeschi, T. (2019) UV irradiation as a comparable method to thermal treatment for producing high quality stabilized milk whey, LWT - Food Science and Technology 105 (2019) 127–134. https://doi.org/10.1016/j.lwt.2019.01.051

Keyser, M., Muller, I.A., Cilliers, F.P., Nel, W., Gouws, P.A. (2008). Ultraviolet radiation as a non-thermal treatment for the inactivation of microorganisms in fruit juice. Innov. Foof Sci. Emerg. Technolog. 2008, 9, 348-354.

Kontopodi, E., Stahl, B., van Goudoever, J. B., Boeren, S., Timmermans, R. A. H., den Besten, H. M. W., Hettinga, K. (2022). Effects of High-Pressure Processing, UV-C Irradiation and Thermoultrasonication on Donor Human Milk Safety and Quality. Frontiers in Pediatrics, 10. doi:10.3389/fped.2022.828448

Koutchma, T. (2009). Advances in ultraviolet light technology for non-thermalprocessing of liquid foods. Food and Bioprocess Technology (2), 138-155.

Mansor, A., Shamsudin, R., Adzahan, N. M., & Hamidon, M. N. (2014). Efficacy of Ultraviolet Radiation as Non-thermal Treatment for the Inactivation of Salmonella Typhimurium TISTR 292 in Pineapple Fruit Juice. Agriculture and Agricultural Science Procedia, 2, 173–180. doi:10.1016/j.aaspro.2014.11.025

Müller, A., Stahl, M. R., Graef, V., Franz, C. M. A. P., & Huch, M. (2011). UV-C treatment of juices to inactivate microorganisms using Dean vortex technology. Journal of Food Engineering, 107(2), 268–275. doi:10.1016/j.jfoodeng.2011.05.026

Pala, C.U.; Toklucu, A.K. (2013). Microbial, physicochemical and sensory properties of UV-C processed orange juice and its microbial stability during refrigerated storage. LWT Food Sci. Technol.

2013, 50, 426–431.

Shah, N.N.A.K.; Rahman, R.A.; Shamsudin, R.; Adzahan, N.M. (2015). Furan development in Dean Vortex UV-CC treated pummelo (Citrus Grandis L. Osbeck) fruit juice. In Proceedings of the International Conference on Sustainable Agriculture for Food, Energy and Industry in Regional and Global Context, Serdang, Malaysia, 25–27 August 2015

Shamsudin, R.; Noranizan, M.A.; Yap, P.Y.; Mansor, A. (2014) Effect of repetitive ultraviolet irradiation on the physico-chemical properties and microbial stability of pineapple juice. Innov. Food Sci. Emerg. Technol. 2014, 10, 166–171.

Sultan, T., Ahmad, Z., Hayat, K., & Chaudhry, I. A. (2021). Computational analysis of three lamp close conduit water disinfection UV reactor. International Journal of Environmental Science and Technology, 19(5), 4393–4406. doi:10.1007/s13762-021-03344-9

Sultan, T., Ahmad, Z., Hayat, K., & Chaudhry, I. A. (2021). Computational analysis of three lamp close conduit water disinfection UV reactor. International Journal of Environmental Science and Technology, 19(5), 4393–4406. doi:10.1007/s13762-021-03344-9

Tran, M. T. T., & Farid, M. (2004). Ultraviolet treatment of orange juice. Innovative Food Science & Emerging Technologies, 5(4), 495–502. doi:10.1016/j.ifset.2004.08.002

Umair, M., Jabeen, S., Ke, Z., Jabbar, S., Javed, F., Abid, M., … Adam Conte-Junior, C. (2022). Thermal treatment alternatives for enzymes inactivation in fruit juices: Recent breakthroughs and advancements. Ultrasonics Sonochemistry, 86, 105999. doi:10.1016/j.ultsonch.2022.105999

Unluturk, S. K., Arastoopour, H., & Koutchma, T. (2004). Modeling of UV dose distribution in a thin-film UV reactor for processing of apple cider. Journal of Food Engineering, 65(1), 125–136. doi:10.1016/j.jfoodeng.2004.01.005

Wang, K., & Xu, Z. (2022). Comparison of freshly squeezed, Non-thermally and thermally processed orange juice based on traditional quality characters, untargeted metabolomics, and volatile overview. Food Chemistry, 373, 131430. doi:10.1016/j.foodchem.2021.131430