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Development of a novel app-based system for the digital color read out of time-temperature-indicators and to monitor shelf life along the chain

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ABSTRACT

The aim of this study was the development of an app-based system for the digital read-out of Time-Temperature-Indicators (TTI) and the shelf life prediction of perishable products. The study was subdivided into four parts: development of a color measurement app for TTIs, investigation of the influence of different environmental and technical parameters on measurement accuracy, development of a kinetic shelf life model for the TTIs by app measurement and the integration of the model and a QR code scanner in the app for shelf life prediction. The study revealed the possibility to perform accurate color measurements by app. Measurement accuracy could be enhanced by white balance correction. Shelf life modeling using the Logistic and Arrhenius models resulted in activation energies from 107.49 to 111.55 kJ/mol for different charging times (1800–500 ms). The app is a promising system for stakeholders to perform temperature monitoring and shelf life prediction along the supply chain.

1. Introduction

Time-Temperature-Indicators (TTIs) are simple and cost-effective tools for temperature monitoring and shelf life prediction along supply chains of perishable goods. The emerging technology provides promising opportunities to enhance food quality and safety as well as to reduce food loss and waste during distribution and at logistics, retailers and consumer level (Ellouze, Gauchi, & Augustin, 2011; Kreyenschmidt, Christiansen, Hübner, Raab, & Petersen, 2010; Taoukis & Labuza, 1989a; Tsironi, Gogou, Velliou, & Taoukis, 2008). The principle of TTIs is based on a simple color change which represents history of time and temperature along storage and indicates cold chain interruptions. For several years, a high quantity of TTI systems was developed (Kerry, O'Grady, & Hogan, 2006; Labuza & Fu, 1995; Taoukis, Koutsoumanis, & Nychas, 1999) and the feasibility of their implementation was shown in studies for, e.g., meat, chicken and fish supply chains (Brizio, A. P. D. R. & Prentice, 2014; Ellouze & Augustin, 2010; Giannakourou, Koutsoumanis, Nychas, & Taoukis, 2005; Tsironi et al., 2008). The interest in the commercialization of intelligent packaging systems is rising even though an overall implementation into processes is difficult despite enhanced computer and information technology (Fang, Zhao, Warner, & Johnson, 2017; Soltani Firouz, Mohi-Alden, & Omid, 2021; Yam, Takhistov, & Miltz, 2005). An efficient temperature monitoring and traceability system with access to real-time data is needed to deliver high quality and safe products, however, standardized data exchange and communication between stakeholders is still challenging but necessary (Eden et al., 2011; Mack et al., 2014; Mercier, Villeneuve, Mondor, & Uysal, 2017; Raab, Petersen, & Kreyenschmidt, 2011). Increasing digitalization and the application of cloud computing services enable real-time shelf life prediction which improves logistic processes and reduces food waste by dynamic pricing strategies (Corradini, 2018; Tamplin, 2018). These advantages compensate for the higher costs of single packaging monitoring. Digital data management in food supply chains is currently mainly based on the use of barcode systems that enable the storage of a high amount of individual data (Ghaani, Cozzolino, Castelli, & Farris, 2016; Kuswandi & Jumina, 2020) like product information on batch, production and packaging date (Mercier et al., 2017; Müller & Schmid, 2019). The combination with intelligent systems can provide additional information about the supply chain, temperature history and finally real-time remaining shelf life based on the TTI discoloration kinetics.

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Color measurements of TTIs are currently either done visually or with high-precise but expensive and elaborate devices, as colorimeters and spectrophotometers. Visual assessment of the TTI color is linked to the comparison with a reference color (Maschietti, 2010; Poyatos-Racionero, Ros-Lis, Vivancos, & Martínez-Máñez, 2018), which is both qualitative and subjective, and furthermore, provides no data which could be integrated in traceability and information management systems. Colorimeters and spectrophotometers require a proper education and handling in a laboratory environment, and the integration into established process controls and stock management is complex. With ongoing digitalization processes, widely distributed smartphones obtain the advantageous property of high-resolution camera systems for color capture (Franca & Oliveira, 2021). Color values of digital images are represented in the RGB (red, green and blue) color space on a pixel level and are more accurate, informative and can be better characterized which facilitates the implementation of standardized color image systems (León, Mery, Pedreschi, & León, 2006). Additionally, smartphones offer a continuous wireless internet connection and cloud computing services which enable the transfer of measured data to standardized traceability systems (Rateni, Dario, & Cavallo, 2017). This is a decisive advantage for TTI read-out solutions, as, beside costs, high entry barriers and complex requirements of heterogenous supply chains (Gao, Tian, Zhu, & Sun, 2020; Ghaani et al., 2016), especially technical barriers (Albrecht et al., 2020; Realini & Marcos, 2014) are the reason for a still missing successful implementation. However, challenges in the use of smartphone cameras are a uniform illumination, the white balance of camera systems as well as varying and constantly changing hardware and software systems (Hunt & Pointer, 2011; Rateni et al., 2017). These challenges must be overcome to implement a reliable and user-friendly app-based read-out system for TTIs to control product quality, support decision processes along the supply chain and to reduce the amount of food waste.

Thus, the aim of this study was the development and investigation of a novel, app-based digital color read-out system for TTIs to control the temperature along the supply chain and to predict remaining shelf life based on TTI discoloration. For this purpose, a color measurement app for TTIs was developed and afterwards tested in storage trials under the influence of various environmental and technical parameters. After a white balance correction of the color values based on the results and further adjustments of the app algorithms, storage trials were conducted to develop a kinetic shelf life model based on the TTI discoloration measured by app. The color measurement app was then further developed to a shelf life prediction app by integrating the model and further measurement parameters like timestamp, geodata and product specific information which can be used for calculating remaining shelf lives along the entire chain. A QR code scanner was additionally integrated to combine color data and information for each product unit and transferring them into a cloud system. Color measurements in the storage trials were parallelly measured by colorimeter as reference.

2. Materials and methods

2.1. Experimental design

The study consisted of four consecutive experimental parts (Fig. 1). At first, a color measurement app was developed to enable a digital read-out of color data of the OnVu™ TTI by smartphones. App measurements were accompanied by a conventional colorimeter as reference in all further steps. In the second part, storage trials with TTIs were conducted to test the influence of different environmental and technical parameters on color measurements by app: TTIs were activated with different charging energies and stored under various constant temperature conditions and different light conditions, measurement distances and smartphone types were tested. Based on that, a corrected calculation of color data by white balancing was defined to reduce the influences of parameters. The trials were conducted by using the OnVu™ TTI labels already available on the market. Additionally, advancements of the TTI design were developed to enable an input into digital systems via QR code. In the third step of the study, storage trials with the OnVu™ TTI were conducted to develop a kinetic shelf life model based on the TTI discoloration measured by app. TTI labels were therefore activated with various charging energies and stored under different constant and dynamic temperatures.

Based on the measurements in step 3, data and shelf life models were integrated into the app in the fourth part to use it as a shelf life prediction tool along the entire supply chain. Besides the TTI measurement, the app comprehends the display of the predicted remaining shelf life and usability features such as a drop-down menu to select the specific supply chain step and a QR code scanner for a correct allocation of color data to specific product information and an individual serial number. All TTI trials were accompanied by an ongoing development process of the app to enhance accuracy of color measurements, i.e., the adjustment of algorithms and an automated color selection.

2.2. General activation and measurement process of the OnVu™ TTI

For all investigations, the OnVu™ TTI (Ciba Specialty Chemicals & Freshpoint, Basel, Switzerland, patent WO/2006/048412) was used. The well investigated label is already on the market and based on a pigmented water ink which is activated by UV-light (Kreyenschmidt, Christiansen, et al., 2010). The color of the label changes from blue to white. The amount of UV light influences the length of the discoloration process and the initial color of the label after activation.

The labels were activated by a UV light charger (GLP 80/56 TTI,

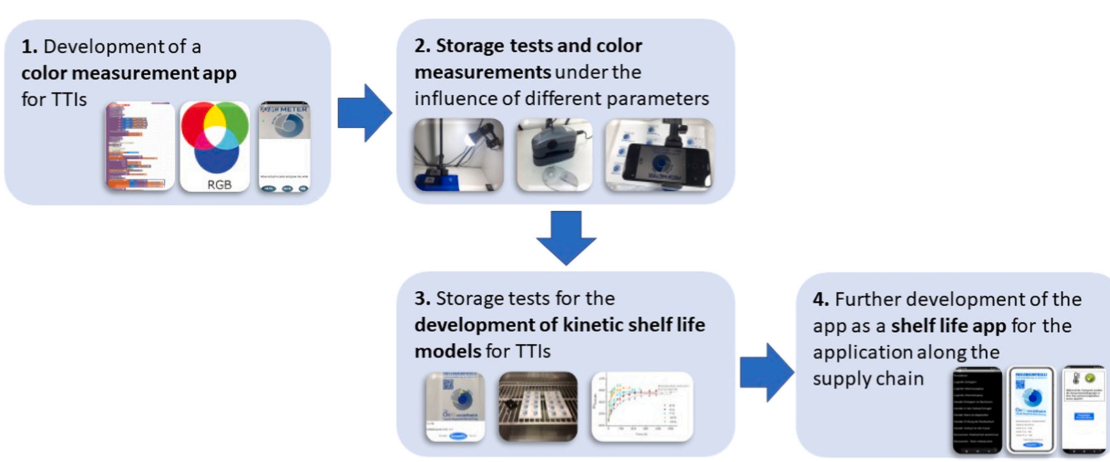

Fig. 1. Process flow of the study.

Bizerba, Germany) in a cooling chamber (Viessmann GmbH & Co KG, Hof, Allendorf, Germany) at $4.0 \pm 0.5\,^{\circ}$C. After activation of the pigmentary water ink in the center of the label, a protective UV-filter (LOT# 000018272) was automatically applied by thermal transfer print. After charging, the labels were placed on precooled glass plates (4 mm thickness) with two layers of self-adhesive white paper to ensure a consistent background for the color measurements. The labels were afterwards stored in high-precision low temperature incubators (MIR 153, SANYO Electric Co., Ora-Gun, Gumma, Japan) at selected temperatures. Temperature and humidity conditions were measured by data loggers (174 H, Testo SE & Co. KGaA, Titisee-Neustadt, Germany) at intervals of 5 min.

The TTI discoloration was measured immediately after charging and at defined interval points during storage. Color measurements by app (from now on referred to as app measurement) were conducted in a darkroom to create a uniform environment for a standardized assessment of the influence of parameters as light and distance on app measurements. Parameters could be adjusted more flexible for a more realistic setting in comparison to illumination chambers and black boxes normally used in laboratory studies (Cruz-Fernández, Luque-Cobija, Cervera, Morales-Rubio, & La Guardia, 2017). For app measurements at daylight conditions a daylight lamp (1620 Lm, 6500 K, Tageslichtlampen24.de, Kiel, Germany) was positioned in a way that sufficient light was provided without casting shadows on the photograph. The smartphones were positioned in a fixed holder to achieve reproducible measurements. The TTIs were positioned in parallel to the smartphone below the lens. As reference values, discoloration of TTIs was measured in CIELAB color system (from now on referred to as reference measurement) by colorimeter EyeOne i1 Basic Pro3 (X-rite Europe GmbH, Regensdorf, Switzerland) using the software i1Profiler v3.3.013493 (X-rite, Inc., Grand Rapids, Michigan, US) for the analysis.

2.3. Experimental parts of the study

2.3.1. Development of a color measurement app for TTIs

The smartphone app was specifically developed for the color measurement of the OnVu™ TTI for Android operating systems and was programmed by using the MIT App Inventor (Massachusetts Institute of Technology, USA). Smartphone and camera specific data are saved on the smartphone when the app is installed by taking an arbitrary picture during the first installation. By starting the app, the camera system of the smartphone is opened automatically, and an instruction appears to take a picture of the TTI and to measure its color values in the RGB color space. After taking the picture of the TTI, the blue dot in the center of the label is selected manually by moving a cursor to the respective position. A white point at the edge of the label is selected by a second cursor which is needed for the white balancing of the raw blue color value to correct the influence of environmental conditions. About 100.000 pixels are gathered depending on the specific smartphone and its settings. Based on the gathered pixels and in combination with the smartphone and camera specific numbers, the app algorithm calculates RGB color values for the blue dot in the center ($R_bG_bB_b$) and the white points on the label ($R_wG_wB_w$). Color values are saved in data files on the smartphone. The app development was accompanied by test measurement procedures of TTIs at different stages of coloration, such as the point of activation and complete discoloration.

2.4. Storage tests with color measurement app and reference system under the influence of different environmental and technical parameters

Storage tests with TTIs were conducted to analyze the influence of different environmental and technical parameters on app measurements, which are charging time, temperature, light, measurement distance and smartphone type. Based on the results, a corrected calculation of color data by white balancing was determined to minimize the influences of parameters on app measurements. For this study part, the OnVu™ TTI label "Fresh-Meter" (Batch 29.08.2014, Color Batch 00552HN8) was used. In total, 60 labels (ten labels for each charging time and temperature) were activated at two different charging times (1800 ms, 1130 ms) and stored at three different isothermal temperatures (4, 7, 15 °C). App measurements in the darkroom were conducted under two different light (daylight lamp, ambient light) and two distance conditions (10 cm distance, 10 cm distance with 2x zoom) by two different Android based smartphones, Nokia 7.2 Dual-SIM Android™ 9.0 48 m pixels (Nokia Oyj, Espoo, Finland) and XIAOMI Mi Note 10 Lite 64 MP quad Camera (Xiaomi Inc., Beijing, China). Each parameter combination of charging time, temperature, light, distance and smartphone type were tested. Consequently, 80 app measurements were made at each investigation point. Reference measurements by colorimeter were conducted at the same investigation points.

Based on app measurements, the medians of the single R, G and B values for the blue dot (*R_b; G_b; B_b*) and the white color point (*R_w; G_w; B_w*) were built. The square value SV_{RbGbBb} for raw color data of the blue dot was then calculated.

$$SV_{R_bG_bB_b} = \sqrt{{R_b}^2 + {G_b}^2 + {B_b}^2} \tag{1}$$

where R_b; G_b; B_b: raw values for the blue dot.

Color data for the blue dot were then corrected by white balance to eliminate influences of investigated parameters. Therefore, measured raw data of R, G and B values for the white color points were each subtracted from the absolute white value 255. The corrected RGB white values were each added to the measured RGB color values of the blue dot.

$$R_c = (255 - R_w) + R_b; G_c = (255 - G_w) + G_b; B_c = (255 - B_w) + B_b \tag{2}$$

where R_c; G_c; B_c: corrected color values by white balance; *255*: absolute white; R_w; G_w; B_w: raw values for the white color points.

The square value SV_{RcGcBc} was then calculated with the corrected RGB color values.

$$SV_{R_cG_cB_c} = \sqrt{{R_c}^2 + {G_c}^2 + {B_c}^2} \tag{3}$$

The square value SV_{LAB} based on the reference measurements was calculated according to Kreyenschmidt, Christiansen, et al. (2010).

$$SV_{LAB} = \sqrt{L^2 + a^2 + b^2} \tag{4}$$

where *SV*: square value; *L*: lightness/luminance; *a*: red and green component; *b*: yellow and blue component of the color.

Based on the measured data, the color measurement app was further improved by adjusting the algorithms used for color measurements. Consequently, the relevant blue and white areas were selected automatically after photographing. The software also evaluated variations of the relevant RGB data, e.g., caused by effects while the TTI was printed, by shadows on the pictures or because the TTI was folded, to calculate the RGB data more reliably.

2.5. Development of a kinetic shelf life model for the OnVu™ TTI based on app measurements

For the implementation in digital processes, a new batch of the OnVu™ TTI ("Frischekontrolle", Batch 21.06.2021, Color Batch 00552HN8) including a QR code was printed which was used for the development of a kinetic shelf life model. Scanning of the serialized QR code by the app after app measurement enables a single-product attribution to the corresponding TTI values as well as the access to individual product information. Consequently, it is possible to transfer and recall color values and product information into a database in a cloud system. The labels were activated at five different charging times (500, 800, 1200, 1500, 1800 ms) and stored at five different isothermal temperatures (2, 4, 7, 10, 15 °C). A dynamic temperature scenario was additionally investigated for labels charged at 800, 1200, 1500 and 1800 ms, the labels were stored at 2 °C for 48 h, 7 °C for 48 h and then 10 °C until the end of storage time. Eight samples were activated and measured for each charging time at each temperature, meaning 232 labels in total. The TTI discoloration of the labels was measured immediately after charging and at defined interval points during storage. App measurements were conducted with the Nokia 7.2 smartphone at constant light and distance conditions (daylight lamp and a 10 cm distance with 2x zoom). Reference measurements were conducted at the same investigation points.

For the development of the shelf life model of the OnVu™ TTI, the kinetic approach as described by Taoukis & Labuza, (1989a, 1989b) and Tsironi et al. (2008) was used. The data were fitted using the software Origin 8 G (OriginLab Corporation, Northampton, MA, USA), using nonlinear regression (Levenberg– Marquardt algorithm).

The discoloration of the TTI by app measurements was described by the development of the RGB and CIELAB square values for app and reference measurements, respectively, as function of time. For both calculations, a logistic model as the primary model was used (Kreyenschmidt, Christiansen, et al., 2010).

$$SV_{LAB;R_cG_cB_c} = \frac{a}{1+e^{-k(t-xc)}} \tag{5}$$

where *a*: amplitude; *k*: reaction rate (h^{-1}); *xc*: reversal point (h); *t*: time (h) for each logistic model in CIELAB and RGB color systems.

The time when a defined discoloration end point was reached, which corresponds to the TTI shelf life, could be calculated with the fitting results by plugging in the discoloration end point. The end point was known as $SV_{End} = 71$ for reference measurements in CIELAB color system (Kreyenschmidt, Christiansen, et al., 2010). For app measurements in RGB color system, the end point was calculated as $SV_{End} = 344$ with a correlation of SV_{Lab} values with the corresponding SV_{RcGcBc} values at different temperatures, using a polynomic trendline.

$$t = \frac{\ln\left(\frac{a}{SV_{End}-1}\right)}{k} + xc \tag{6}$$

where SV_{End}: 71 for TTI shelf life calculation in CIELAB color system, 344 in RGB color system.

The temperature dependency of the TTI discoloration in each color system was described using the Arrhenius equation (modified after Arrhenius, 1889) as secondary model and plotting the calculated reaction rate k as a function of temperature.

$$\ln(k) = \ln(k_0) - \frac{E_a}{R} \bullet \frac{1}{T} \tag{7}$$

where *k*: reaction rate (h^{-1}); k_0: constant (h^{-1}); E_a: activation energy (kJ mol^{-1}), *R*: ideal gas constant (8.314 J mol^{-1} K^{-1}); *T*: absolute temperature (K).

2.6. Development of the app as a shelf life predicting tool

Based on the parameters of the developed kinetic shelf life model, the app was finally adjusted to predict the shelf life based on TTI color values. Kinetic model parameters were included into the app to calculate remaining shelf lives for different temperatures. The app was further extended by a drop-down menu prior to the photographing to select a user profile, i.e., production, logistic, retailer, consumer. Furthermore, an app-specific cloud database was constructed. The serialized QR code of the TTI label is scanned automatically by using the app. Thus, the serialized number of the QR code is used to get product specific parameters necessary for the shelf life model out of a database via internet. For each scanning process of the same TTI with its serialized QR code, a new data set with the new color values and updated parameters is saved in the same database, related to the serial number within the QR code. For the use of the shelf life app, an internet connection is required.

3. Results and discussion

3.1. Development of a color measurement app for TTIs

The developed algorithms focused on different data processing steps after a TTI picture was taken: the identification of RGB color values in the blue dot, the localization of the color circle surrounding the blue dot as well as representative white areas on the label, and the storage of identified RGB values in data files to be usable for further calculations. Results showed that the development of a color measurement app was successfully reached. The app is in general able to detect and measure individual R, G and B values of the TTI and to reflect variances in color values. The change of color values in RGB system from blue at the activation point to complete discoloration was measurable by app. Therefore, the behavior of app measurement conformed to the typical measurement by colorimeter in CIELAB color system which is the current standard method (Albrecht et al., 2020; Gao et al., 2020; Kreyenschmidt, Christiansen, et al., 2010). Thus, the basic prerequisites for a successful app measurement of the TTI color are given. It can be assumed that color measurements with a smartphone app are sensitive enough to reliably measure discoloration of TTIs along time.

3.2. Storage tests with color measurement app and reference system under the influence of different parameters

App measurements revealed that raw color values in the blue dot of the label under the influence of the different parameters light, distance and smartphone type showed moderate to high variations. Raw color values in the blue dot measured under the influence of the different parameters were pooled to reflect their overall variation[1]. This is shown exemplary for selected points of time for measurements at 7 °C in Fig. 2a. Here, raw SV_{RbGbBb} values were in a range from 94.46 to 183.29 at the initial charging point and 217.46–312.58 after 360 h. Concerning light conditions, measurements at daylight (lamp) showed higher color values over time than at

ambient light (see Appendix, Table A.1). Also, measurements with 2x zoom showed higher color values than with the usual distance of 10 cm at the same light conditions. Measurements by Xiaomi showed tendentially higher color values than by Nokia, however, in the later course of storage time, values are increasingly approaching each other. Highest variations are shown for measurements at ambient light with Nokia compared to measurements at daylight lamp conditions and zoom with Nokia in all scenarios at different charging times and temperatures.

The high variance in the results for raw RGB data of the blue dot indicated that an inclusion of the white balance and the correction of app measurements was necessary to reduce the parameter influences. The high quantity of data generated by the multiple app measurements at different conditions were the basis for developments in measurement corrections and app improvements. The app measurement correction by white balance, also shown in Fig. 2a as pooled data for the different parameter conditions, showed a clear reduction of data variance when compared to raw data at 7 °C. Corrected SV_{RcGcBc} were in a range from 230.21 to 270.46 at the initial charging time and 362.01–414.84 at 360 h. The differences in the absolute numbers result from the correction of measurements. The courses of discoloration at different parameter settings are shown in Fig. 2b, exemplary for 1800 ms charging time and storage at 7 °C. Initial SV_{RcGcBc} color values ranged from 232.81 ± 3.42 for Nokia at ambient light to 263.88 ± 2.97 for Xiaomi at daylight lamp with 2x zoom. SV_{RcGcBc} color values after storage of 479 h at 7 °C ranged from 395.15 ± 9.13–406.20 ± 5.82 for Nokia at ambient light and Xiaomi at ambient light, respectively. Corrected color values

[1] Results for measurement at daylight conditions (10 cm distance) with Xiaomi could not be calculated for all investigations, as values for the white color points were not detected by the picture.

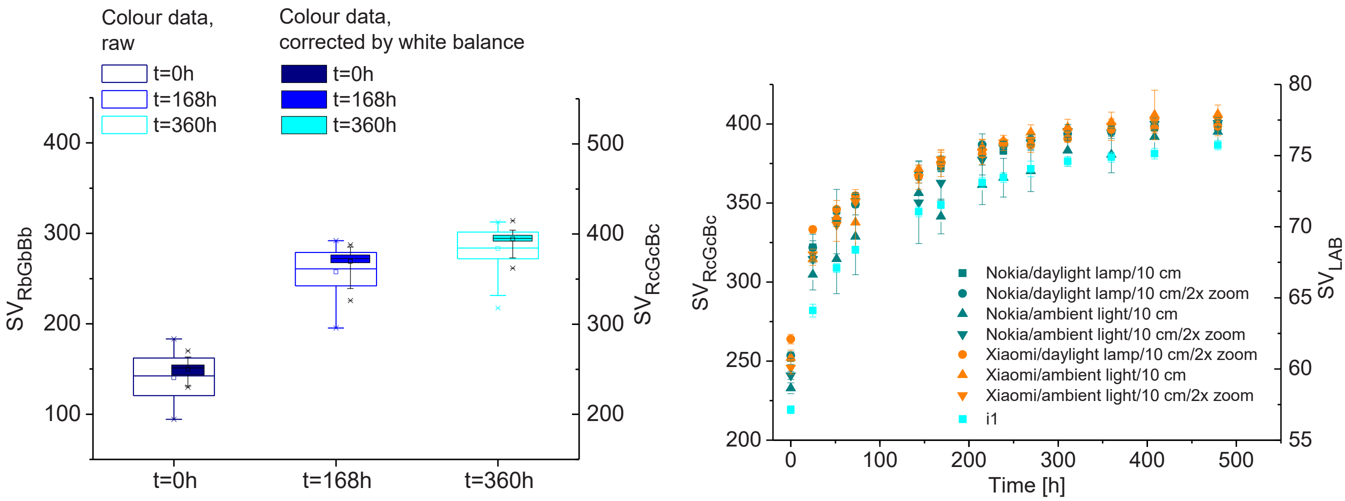

Fig. 2. (a) Boxplots of raw color data and color data corrected by white balance measured by app and (b) Comparison of TTI discoloration measured by app at different ambient and smartphone conditions and by colorimeter at different points of time during storage at 7 °C (TTI charging time: 1800 ms).

are still higher measured at daylight than at ambient light conditions, however, differences are remarkably reduced. Differences in distance could be nearly compensated by data correction. App measurements by Nokia at the different conditions were still generally lower than by Xiaomi, but differences were strongly reduced. Furthermore, overall variances for corrected values at the different parameter settings decreased throughout the storage time, assuming that the sensitivity decreased at high discoloration. However, this range in which the TTI is already discolorated is not relevant for the shelf life prediction. Additionally, SV_{RcGcBc} values showed good reproducibility for constant temperatures in all investigations with standard deviations (SD) in a range from 1.41 to 10.04 immediately after charging (0 h) and 0.78–30.85 for the entire app measurement points. For reference measurements with colorimeter, stable and reproducible TTI color values were already presented by Kreyenschmidt, Christiansen, et al. (2010). SDs are higher for app measurements, however, 75% of SDs are under 4.34 for start values at 0 h and under 7.46 for entire measurements. A further optimization of the app could achieve the measurement of more stable color values. The influence of these variances on a later shelf life prediction depends on the environmental conditions and the regarded product and must be investigated in practical studies. In general, it can be assumed that the calculation via subtraction of white balance is a reliable way to correct app measurements. Also Park, Baynes, Cho, & Yoon (2014) and Lee, Baek, Kim, and Seo (2019) applied a normalizing of RGB color measurements with white background when investigating paper microfluidics and freshness indicators, respectively. Prior to the definition of the correction with white balance in this study, various calculation paths were analyzed. The calculation determined in Eq. 2 showed the best adjustment of RGB values when comparing the results of the different parameter combinations. Smartphone and camera specific data were already taken into account in measurements when installing the app. However, it must still be considered that there is a complexity of influencing factors on app measurements based on the individual properties of camera systems and smartphones. One solution to further optimize app measurements and reduce variation due to influencing parameters is to implement a smartphone and camera specific correction factor which automatically corrects measurements after photographing.

It can be further concluded that a reproducible and reliable setting of the initial color values can be also validated by app measurement. The application of a smartphone is even more advantageous due to the detection of the whole blue color dot by photographing; most conventional colorimeters only gather a smaller, more unrepresentative surface area (León et al., 2006; Papadakis, Abdul-Malek, Kamdem, & Yam, 2000; Segnini, Dejmek, & Öste, 1999).

3.3. Development of a kinetic shelf life model for the OnVu™ TTI based on app measurements

Fig. 3a and b show the discoloration processes of the TTI initially charged for 1800 ms and stored at different constant temperatures by app measurements as well as in comparison to reference measurements. The course of the discoloration curves is in general comparable to the results in the previously described experimental part. Furthermore, the distinction of initial charging values and associated discoloration times could be reliably reached by app measurements in all investigations. The results are exemplary shown in Fig. 3c for charging times at 7 °C, Fig. 3d shows results of reference measurements. Results of the dynamic temperature scenario also showed that temperature fluctuations – as they can occur under real supply chain conditions – could be reflected by the app. The kinetic shelf life models based on app measurements could be likewise generated with the same logistic regression as reference measurements. This is the basic requirement for the application of the app as detection device, as kinetics are detectable and shelf life measurements are possible. Discoloration curves generated by app measurements flattened out faster and plateaus are reached earlier along time when compared to reference measurements. Consequently, discoloration end points were partly not reached at high charging times and low temperatures in the applied storage time. Results indicate that the RGB color system is less sensitive for changes in the lighter color range. The less sensitivity can limit the range in which the model based on app measurements could be reliably used for shelf life prediction, which means that at very high charging times and low temperatures, a shelf life prediction is currently limited. The lower sensitivity of smartphones compared to high-precise, analytical devices is another limitation in the applicability. Also extreme light conditions can influence the accuracy of the measurements. One possibility would be to indicate suitable conditions, like other sensitive measuring systems. However, in general, the results showed that the TTI color measurement by an app-based read-out system is possible, which is a milestone in the development of easy-to-use TTI systems in practice. An optimization of the models could enhance the accuracy of the shelf life prediction and thus, could make the system more applicable in terms of safety.

The kinetic behavior of the TTI with its discoloration measured by app is shown in Fig. 4a as the temperature dependency of the reaction rate based on the Arrhenius approach. Results for ln(k) at different temperatures were fitted by linear regression. The lines ran almost parallel to each other, depending on the individual charging time. Linear

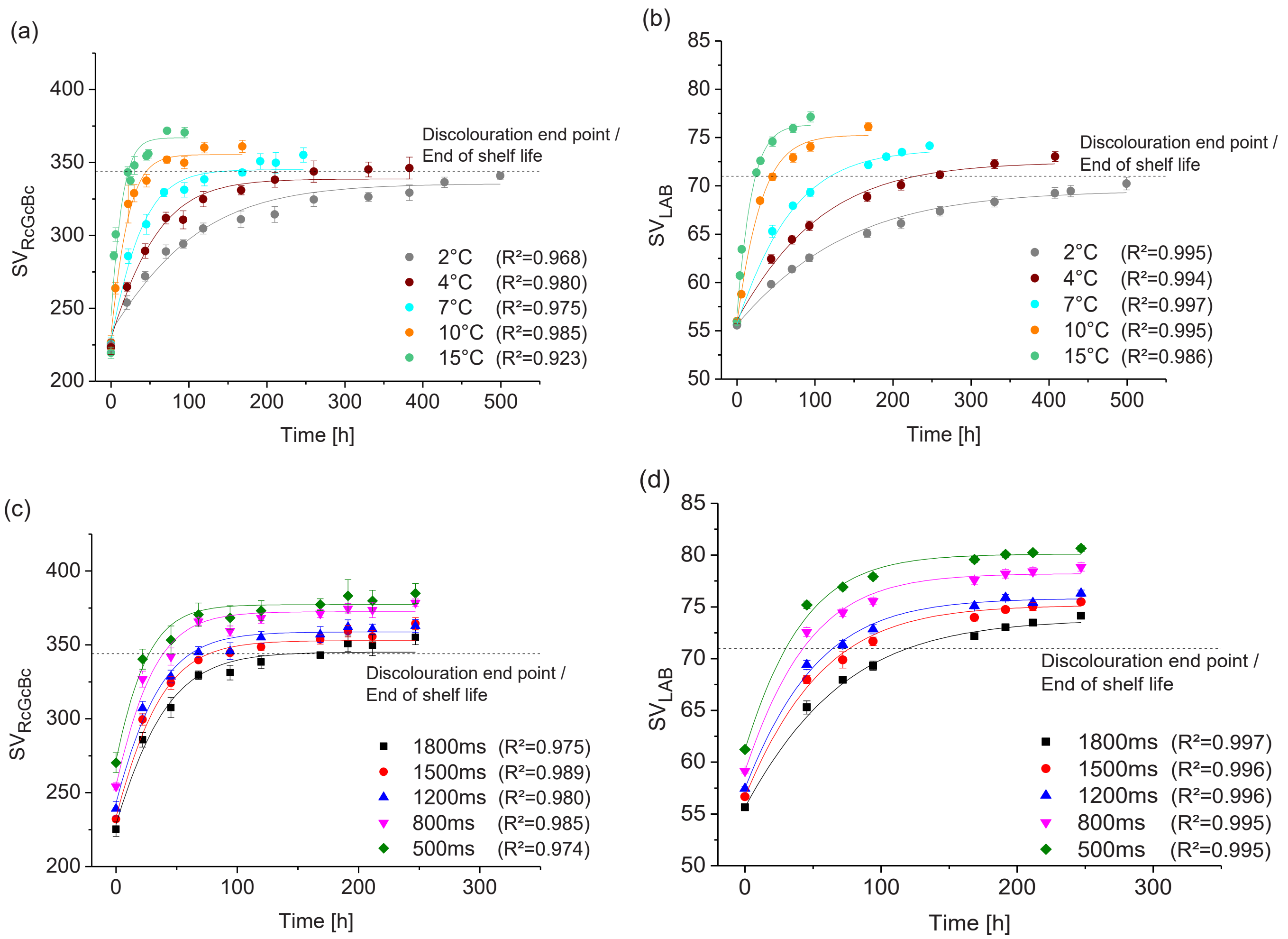

Fig. 3. Discoloration of the TTI stored at different temperatures for a charging time of 1800 ms, measured by app (a) and colorimeter (b) and discoloration of the TTI by using different UV charging times stored at 7 °C, measured by app (c) and colorimeter (d).

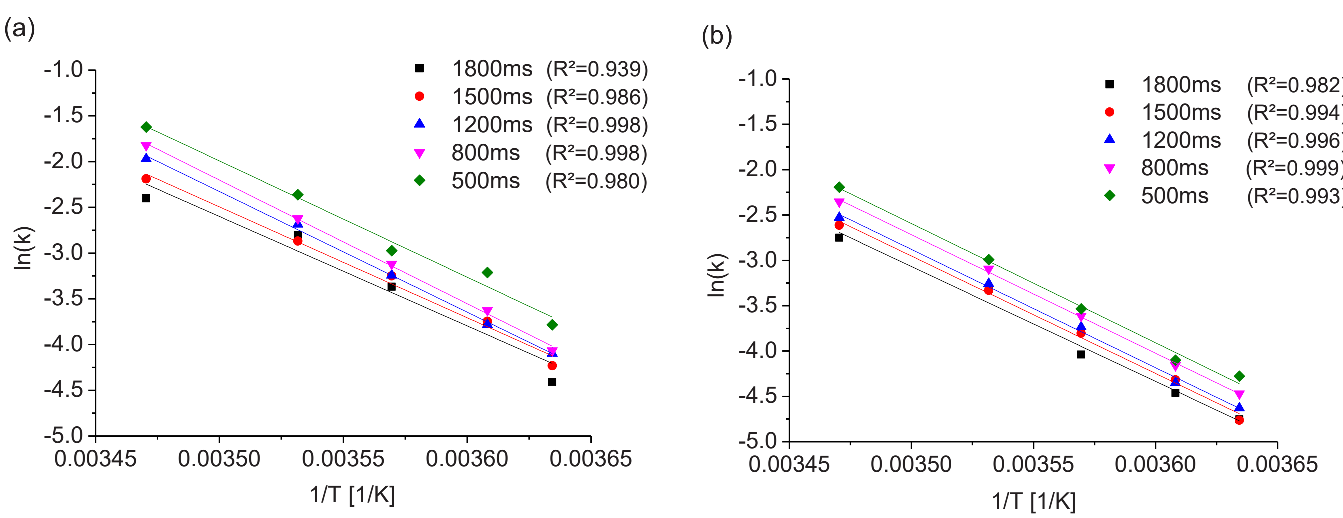

Fig. 4. Arrhenius plot showing TTI temperature dependency of the reaction rate (*ln (k)*) at different charging times for measurement with app (a) and colorimeter (b).

fits for 1800–800 ms converged with lower temperature dependency. The Arrhenius model for parameters resulting from reference measurements showed comparable linear fits (Fig. 4b). Values for ln(k) were higher for app measurements with − 1.62 to − 4.41 when compared to reference measurements with − 2.19 to − 4.75. Results are not directly comparable due to the different color systems resulting in different number ranges for model parameters a, xc and k. However, the slopes of the linear fits were in a similar range (Table 1(1)), which is the basic

Table 1
(1) Kinetic parameter of the OnVu™ TTI and R^2 values for constant temperature conditions at different charging times for measurement with app and colorimeter, (2) Shelf life of TTI calculated by app and colorimeter measurements for different constant temperature conditions at different charging times.

(1)

Charging time [ms]	TTI measurements with app [SV_{RcGcBc}]			TTI measurements with colorimeter [SV_{LAB}]		
	Slope	E_A [kJ mol^{-1}]	R^2	*Slope*	E_A [kJ mol^{-1}]	R^2
1800 ms	-12667.11	107.49	0.982	-11260.1	101.46	0.939
1500 ms	-12945.76	109.83	0.994	-12199.24	103.51	0.986
1200 ms	-13046.43	110.71	0.996	-13182.46	111.84	0.998
800 ms	-13065.08	110.83	0.999	-13516.21	114.68	0.998
500 ms	-13145.83	111.55	0.993	12710.27	107.86	0.980

(2)

Charging time [ms]	TTI shelf life based on app measurements [h]						TTI shelf life based on colorimeter measurements [h]					
	2 °C	4 °C	7 °C	10 °C	15 °C	dyn	2 °C	4 °C	7 °C	10 °C	15 °C	dyn
1800 ms	-	-	145	46	22	140	-	229	120	44	24	149
1500 ms	-	159	77	42	18	138	451	153	77	39	18	137
1200 ms	-	116	61	28	13	108	275	130	65	31	14	111
800 ms	128	73	39	22	9	97	197	94	43	22	10	90
500 ms	70	44	27	13	6	N/A	102	60	30	15	7	N/A

prerequisite for the calculation of the activation energies as the expression of the temperature dependency of discoloration. The activation energies for the different charging times calculated based on app measurements were in a range from 107.49 to 111.55 kJ/mol. Activation energies calculated based on reference measurements differed from 101.46 to 114.68 kJ/mol. The similarity of calculated results proves that the discoloration process and the kinetic behavior of the TTI could also be mirrored and reliably calculated by the app. Kreyenschmidt, Christiansen, et al. (2010) reported activation energies in a range from 92,9 to 105.9 kJ/mol by colorimeter measurements. Slightly higher activation energies in this study may be due to a different range of charging times and the usage of novel printed batches of the OnVu™ TTI, resulting in differing discoloration times and thus, in various kinetic parameters.

It is known that activation energies of TTI and the monitored food should not differ more than 20 kJ/mol (Taoukis et al., 1999). The calculated activation energies based on app measurements also fulfilled the requirements for the TTI to be applied as a temperature monitoring tool for perishable products. The TTI characterized by app measurements can thus represent a wide variety of perishable products in the range of comparable activation energies. This includes aerobe packed fresh poultry with 101.3-102.9 kJ/mol (Bruckner, Albrecht, Petersen, & Kreyenschmidt, 2013; Raab et al., 2008), cooked meat products with 109.9-115.9 kJ/mol (Kreyenschmidt, Hübner, et al., 2010; Mataragas, Drosinos, Vaidanis, & Metaxopoulos, 2006), MA packed fish 106.7 kJ/mol (Labuza, Fu, & Taoukis, 1992) as well as ready-to-eat meals with 105.58 kJ/mol (Haouet et al., 2018), calculated based on the individual spoilage kinetics of the products.

3.4. Development of the app as a shelf life predicting tool

Shelf lives calculated by app and reference measurements are shown in Table 1(2). Differences in shelf lives between app and reference measurement varied between 69 h and 0 h, differing rather at 2–4 °C (6–69 h) than at 7–15 °C (0–2 h). This could be based on differences in linear fits and increased slopes of the discoloration kinetics by app measurement in the first half of the storage time at lower temperatures. At higher temperatures, the curves are more similar to reference measurements. Also at the dynamic scenario, shelf lives at different charging times had low differences between 1 and 9 h. Further developments in the camera and app technologies may enhance the color sensitivities and improve the reflection of TTI discoloration kinetics. There are already developments in the field of app-based TTI read-out and for barcode scanning, as for the Smartdot TTI (Evigence, 2022) and the Smart Tag™ (Freshcode) (Packaging Journal, 2019), respectively. Chen et al. (2017) also showed that a digital read-out of food sensors by smartphone is possible and gives reliable information about food spoilage. It is generally conceivable that the developed app can also be applied for other TTI systems with a color-based response. These could include systems based on discoloration or color change, such as described for the Vitsab® Smart Labels (Chun, Choi, Lee, & Hong, 2013; Tsironi, Giannoglou, Platakou, & Taoukis, 2016) or newly developed TTI materials as studied by Xu, Ge, Li, Lin, and Mao (2017) and Brizio & Prentice (2015). The conversion of previously applied color response based on CIELAB system to RGB system as a digital response is mandatory.

The increased popularity of smartphones as a simple, time- and cost-effective digital picture and data recording device can revolutionize the developments in intelligent packaging research (Poyatos-Racionero, Ros-Lis, Vivancos, & Martínez-Máñez, 2018), especially when combined with big data and cloud computing (Kalinowska, Wojnowski, & Tobiszewski, 2021). The visual TTI assessment has an influence on the consumer behavior and product handling and could provoke rejection and cherry-picking effects (Müller & Schmid, 2019; Rossaint & Kreyenschmidt, 2015), but the objective analysis by using a smartphone – as a well-established device – may enhance consumers' trust. Furthermore, hurdles in implementation, such as additional costs and a simple operation for the stakeholders, are relatively low. The promising application of smartphones as color and image analysis tools was already shown in other studies, especially for the assessment of food quality parameters (Franca & Oliveira, 2021), such as fat contents (Cruz-Fernández et al., 2017), ethanol concentration in alcoholic beverages (Böck, Helfer, Da Costa, Dessuy, & Ferrão, 2018; Marinho, Lima, Rocha, Reis, & Kamogawa, 2019) or quality assessment of tea (Li et al., 2021). Digital imaging with smartphones was also studied for indirect food control, such as freshness indicators and paper-based assays (Lee, Baek, et al., 2019; Lee, Park, et al., 2019; Shen, Hagen, & Papautsky, 2012).

Fig. 5 shows the overall shelf life app system developed in this study which combines different functionalities that may be used along the supply chain of perishable products: Products are packed and labelled with TTIs including the QR code which enables an individual serial number, whereby traceability of single products can be realized (Kalpana, Priyadarshini, Maria Leena, Moses, & Anandharamakrishnan, 2019). The producer is authorized to enter product and batch specific information via the web application into a data base for the defined TTIs and serial numbers used for this batch. This includes product shelf life data necessary to estimate the remaining shelf lives along the chain; it also may include additional information for marketing or logistic activities of stakeholders. While scanning the QR code, the app is connected via internet to a database and user information, the current location, a timestamp, and product specific information are added to the TTI serial numbers. The app can be customized for different

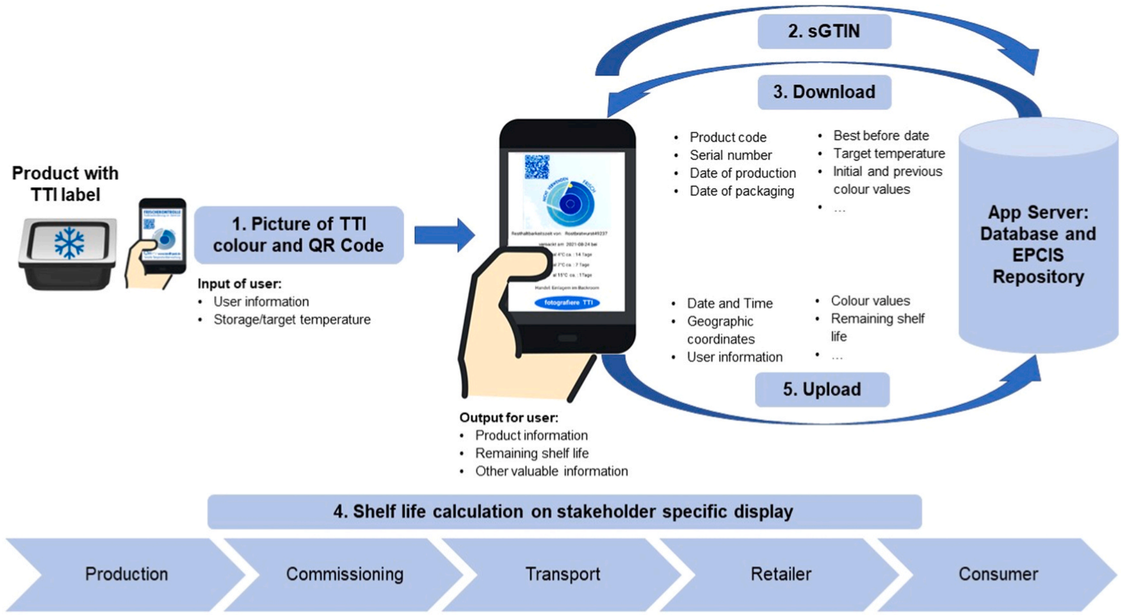

Fig. 5. Overview of the app system for smartphone application along the supply chain of perishable food products.

stakeholders, as logistic partners, wholesalers, or customers, by adjusting different information access, functionalities, authorizations, and outputs. The provision of valuable supply chain information for relevant stakeholders makes the entire supply chain more transparent and can thus optimize processes. Combining TTI systems with barcodes enables the integration of more useful information complementing the color measurements which optimizes the whole temperature monitoring process (Fang et al., 2017; Wang et al., 2015).

4. Conclusions

In this study, a novel app-based system for the color measurement and shelf life prediction of TTIs was developed. It was found that a reliable app measurement with digital imaging of TTIs is possible by a white balanced calculation of RGB color values. The kinetic shelf life model based on TTI discoloration by app measurement showed comparable results in activation energies compared to the reference measurements by colorimeter. The inclusion of a QR code into TTI systems provide a remarkable benefit concerning the connection with product-specific data and the transfer of measured color values and other real-time supply chain data into a cloud. The integration of the kinetic shelf life models into the app-based system could enable the use of the app as a shelf life prediction tool, which allows stakeholders along the entire chain to monitor temperature and predict remaining shelf lives by applying a smartphone as a simple measurement device. Therefore, further investigations concerning model validation and tests under real chain conditions are necessary. Further studies should examine if perishable products can be covered by the developed system. Therefore, detailed knowledge on the products is necessary, and the TTI must be customized to the product's and chain specific requirements. Thus, the app not only represents a user friendly but also a time effective solution for actors along food supply chains. The implementation of app-based TTI systems can further support the emerging idea of dynamic shelf lives.

Relationships

There are no additional relationships to disclose.

Patents and intellectual property

There are no patents to disclose.

Other activities

There are no additional activities to disclose.

CRediT authorship contribution statement

Claudia Waldhans: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing – Original Draft, Writing – Review & Editing. Rolf Ibald: Conceptualization, Methodology, Software, Investigation, Analysis, Writing – Original Draft, Writing – Review & Editing. Antonia Albrecht: Funding acquisition, Conceptualization, Methodology, Software, Writing – Review & Editing. Dirk Wollenweber: Software, Investigation, Analysis, Writing – Review & Editing. Su-Jen Sy: Writing – Review & Editing. Judith Kreyenschmidt: Funding acquisition, Project administration, Supervision, Writing – Review & Editing.

Declaration of Competing Interest

None.

Data Availability

The data that has been used is confidential.

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Appendices

Table A.1
Mean raw SV_{RbGbBb} values for TTIs measured under the influence of different parameters, activated with 1800 ms and stored at 7 °C.

		0 h		168 h		360 h	
		Light conditions					
Smartphone	Distance	Daylight	Ambient	Daylight	Ambient	Daylight	Ambient
Nokia 7.2	10 cm	145.58 ± 4.92	104.89 ± 4.76	256.30 ± 7.36	205.81 ± 7.25	279.02 ± 3.35	240.41 ± 13.70
	2x zoom	165.59 ± 4.51	120.20 ± 3.35	288.71 ± 3.66	257.65 ± 9.16	308.48 ± 2.92	282.80 ± 6.47
XIAOMI Mi Note 10 Lite	10 cm	-	122.47 ± 3.21	-	243.19 ± 6.78	-	271.11 ± 7.03
	2x zoom	179.87 ± 2.32	145.10 ± 5.66	281.94 ± 4.52	272.73 ± 3.70	300.00 ± 2.51	302.23 ± 3.85

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