

## Article

# Antioxidant Active Packaging Films Based on Oat Straw Cellulose and Resveratrol for Sustainable Food Packaging

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## Abstract

The extensive use of petroleum-based plastics in food packaging has raised environmental concerns, increasing interest in biodegradable materials derived from renewable resources. Cellulose-based films from agricultural residues offer a sustainable alternative, and incorporating bioactive compounds can provide active packaging functionality to enhance food preservation. In this study, resveratrol was incorporated into oat straw-derived cellulose films to develop biodegradable active packaging materials. Films with varying concentrations of resveratrol were prepared and evaluated for physical, mechanical, barrier, optical, antioxidant, biodegradation, and fruit preservation properties. Resveratrol significantly enhanced the films' antioxidant activity, increasing radical-scavenging activity from 4.05% in the control film to 19.70% in the film containing 0.7% resveratrol. The films also exhibited improved ultraviolet light-blocking properties while maintaining comparable moisture content, water solubility, mechanical properties, water vapor permeability, and biodegradation behavior. All films showed rapid soil biodegradation, with more than 80% weight loss after 33 days. During grape storage, the resveratrol-containing film maintained the fruit quality by moderating changes in weight loss, total soluble solids, titratable acidity, and ascorbic acid content, while avoiding the quality deterioration observed in polystyrene-covered grapes during storage. These findings demonstrate that oat straw-derived cellulose films containing resveratrol combine antioxidant activity, ultraviolet light protection, biodegradability, and improved preservation performance during grape storage. The developed films show promise as sustainable antioxidant active packaging materials for fresh-produce applications.

**Keywords:** active packaging; antioxidant; agricultural residues; biodegradable films; shelf-life extension



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## 1. Introduction

Plastic materials are widely used in food packaging because of their low cost, mechanical strength, processability, and ability to protect products from physical and environmental damage. Global plastic production exceeded 400 million tons in 2022, yet only a small fraction is recycled, while the majority accumulates in landfills or the environment [1–4]. The persistence of plastic waste contributes to ecological degradation and the formation of micro- and nano-plastics, which have been detected in food-contact materials and environmental systems [5–9]. In addition, certain plastic additives, including bisphenol A

and phthalates, have been associated with adverse health effects [10–13]. These environmental and health concerns have accelerated interest in renewable and biodegradable alternatives for food-packaging applications. Cellulose-rich agricultural residues represent an abundant and underutilized resource for producing biodegradable packaging materials [14–20]. Cellulose-based films possess favorable film-forming characteristics and can serve as sustainable alternatives to petroleum-derived plastics. Beyond reducing dependence on conventional plastics, such materials can also contribute to food preservation by helping maintain product quality and extend shelf life, thereby reducing food losses throughout the supply chain [21].

To further improve the performance of biodegradable packaging materials, active packaging strategies have gained considerable attention. Active packaging systems are designed to interact with the packaged food or its surrounding environment through the incorporation of functional compounds within the packaging matrix [22–26]. Depending on the incorporated additive, these systems can provide antioxidant, antimicrobial, oxygen-scavenging, or moisture-regulating functions that help maintain product quality during storage [27–34]. Numerous studies have demonstrated the successful incorporation of bioactive compounds into biopolymer films to enhance their functionality. For example, passion fruit essential oil improved the properties of fish protein-based films [35], thymol and carvacrol enhanced the preservation performance of starch films used for cheese packaging [36], and plant-derived extracts increased the antioxidant activity of starch-, cellulose-, and chitosan-based films [37–39]. These findings highlight the potential of natural bioactive compounds to transform biodegradable films into multifunctional packaging materials.

Among the various bioactive compounds investigated for active packaging applications, resveratrol attracted interest in its potent antioxidant activity [40–44]. Resveratrol is a naturally occurring polyphenol found in grapes and other fruits that exhibits strong free-radical scavenging capacity [45]. Its antioxidant effectiveness has been reported to exceed that of several conventional antioxidants, including ascorbic acid, propyl gallate, and  $\alpha$ -tocopherol [46]. Incorporation of resveratrol into biopolymer matrices has been shown to improve antioxidant functionality and food preservation performance. For example, resveratrol-loaded pectin–fish gelatin films exhibited enhanced radical-scavenging activity, while resveratrol/ $\beta$ -cyclodextrin complexes improved the antioxidant and antibacterial properties of microcrystalline cellulose–starch films [46,47]. Similarly, starch–gelatin films [48], chitosan–methylcellulose films [49], and carboxymethyl cellulose films [50] also exhibited excellent antioxidant activity when incorporating resveratrol. These promising results suggest that resveratrol may serve as an effective active ingredient for the development of sustainable packaging systems based on agricultural biomass.

Fresh grapes are highly perishable commodities because they continue to respire after harvest and are susceptible to quality deterioration from oxidative processes, moisture loss, and microbial spoilage during storage. Effective packaging should therefore provide an appropriate balance between gas exchange and moisture transfer while protecting fruit from oxidative deterioration. Packaging materials with antioxidant activity and ultraviolet light-blocking capability may help preserve quality attributes such as ascorbic acid, titratable acidity, and soluble solids while maintaining fruit appearance and extending marketability. Consequently, grapes provide an appropriate model system for evaluating the performance of active biodegradable packaging materials. Accordingly, evaluating changes in weight loss, soluble solids, titratable acidity, and ascorbic acid provides an integrated assessment of the effectiveness of active packaging during postharvest storage.

Among the various agricultural residues available for packaging, oat straw is an abundant byproduct with a substantial cellulosic fraction suitable for film production. Valorizing such residues into high-value packaging materials is an important strategy for advancing circular bioeconomy objectives. Although resveratrol has shown promise as an active ingredient in several biopolymer films, its interaction with oat straw-derived cellulose and the resulting effects on film functionality remain unclear. Because incorporating active compounds can alter film structure, physicochemical properties, antioxidant performance, and food-preservation efficacy, understanding these effects is essential for developing functional packaging materials from agricultural residues. Therefore, this study aimed to develop biodegradable oat cellulose films containing resveratrol and to evaluate their physical, mechanical, barrier, antioxidant, optical, biodegradation, and fruit-preservation properties. It was hypothesized that incorporating resveratrol into oat straw-derived cellulose films would confer antioxidant activity and enhanced ultraviolet protection while preserving the desirable gas permeability of the cellulose matrix. Collectively, these characteristics were expected to improve the storage stability of grapes by slowing oxidative deterioration of quality while maintaining an appropriate packaging atmosphere. The findings provide insight into the feasibility of using oat straw-derived cellulose as a carrier for bioactive compounds, thereby supporting the development of value-added packaging materials from agricultural residues and advancing circular bioeconomy strategies.

## 2. Materials and Methods

### 2.1. Materials

Oat straw was collected from Watertown, South Dakota. Sodium hydroxide (NaOH), zinc chloride ( $\text{ZnCl}_2$ ), calcium chloride dihydrate ( $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ ), sorbitol, calcium sulfate ( $\text{CaSO}_4$ ), and potassium sulfate ( $\text{K}_2\text{SO}_4$ ) were purchased from VWR International (Radnor, PA, USA). Resveratrol (#R0071) was procured from Tokyo Chemical Industry, Portland, OR 97203, USA. Ethanol was bought from the Department of Physics, Chemistry and Biochemistry, South Dakota State University, Brookings, SD, USA.

### 2.2. Extraction of Cellulosic Residue and Film Preparation and Characterization

Oat straw was dried and milled to pass through a 60-mesh screen. The material was treated with 5% KOH at 35 °C for 12 h, then with 3%  $\text{NaClO}_2$  at 60 °C for 6 h. During bleaching, the pH was maintained at 5 with 10% glacial acetic acid. The resulting material was washed with distilled water until neutral pH and then dried at 30 °C [51]. The extraction yielded approximately 37% cellulosic residue. The dried cellulosic residue was ground to a 60-mesh powder and stored in airtight containers at room temperature until use.

Cellulosic residue powder (0.4 g) was mixed with 1.6 mL of distilled water and allowed to swell at 65 °C for 1 h. The swollen material was dissolved in a 68%  $\text{ZnCl}_2$  solution (16.24 g  $\text{ZnCl}_2$  in 6 mL of distilled water) in a vial and transferred to an 83 °C water bath. After 30 min,  $\text{CaCl}_2$  was added to a final concentration of 400 mM (7.6 mL of total water system), and the mixture was maintained for 10 min. Glycerol (10%) was then incorporated as a plasticizer. Resveratrol solutions (0.1, 0.3, 0.5, and 0.7 mg/mL) were prepared separately, and 0.5 mL of each was added to the film-forming mixture. A film prepared without resveratrol served as the control. The resulting solutions were hand-cast, regenerated with ethanol, framed, washed with distilled water, and dried at room temperature. The dried films were stored under ambient conditions until characterization.

The films were characterized for moisture content, water solubility (WS), color, transparency, UV-Vis-IR light transmittance, absorption coefficient, antioxidant activity, FTIR,

water absorption and absorption kinetics, tensile strength, elongation at break, water vapor permeability, biodegradation and degradation kinetics, and fruit preservation performance using established methods [52]. Moisture content was measured by drying the films in an oven at 110 °C for 24 h and calculated using Equation (1). WS was determined by immersing pre-dried films in water with agitation at 175 rpm for 24 h, followed by oven drying for an additional 24 h. Equation (2) was used for calculating the film's WS.

$$\text{Moisture}(\%) = \left( \frac{\text{Initial weight} - \text{Weight after drying}}{\text{Initial weight}} \right) \times 100 \quad (1)$$

$$\text{Water solubility}(\%) = \frac{(\text{Initial dried weight} - \text{Final dried weight})}{\text{Initial dried weight}} \times 100 \quad (2)$$

Film color was measured on the Hunter scale L, a, b, using a Nix Pro 2 color sensor (Model no: NIXPRO002, Nix Sensor Ltd., Hamilton, ON, Canada). Further, the film's whiteness index (WI), yellowness index (YI), and total color difference (TCD) were calculated using Equations (3), (4), and (5), respectively. Optical transparency was evaluated by measuring transmittance at 600 nm using a UV-Visible spectrophotometer (Model UV-1600PC, 10037-436, VWR International, Radnor, PA, USA), while spectral transmittance across the UV-Vis-IR region was recorded from 190 to 1060 nm. The transparency and absorption coefficient were determined using Equations (6) and (7), respectively. FTIR spectroscopy was performed over the range of 400–4000 cm<sup>−1</sup> using 36 scans at a resolution of 4 cm<sup>−1</sup> to characterize the functional groups present in the films. The antioxidant capacity of the films was assessed using the DPPH radical scavenging assay (RSA), and IC<sub>50</sub> values were determined. Equation (8) was used for the calculation of RSA, and a linear curve was used for the IC<sub>50</sub> value determination.

$$\text{WI} = 100 - \left[ (100 - L^*)^2 + a^{*2} + b^{*2} \right]^{0.5} \quad (3)$$

$$\text{YI} = 142.86 \frac{b^*}{L^*} \quad (4)$$

$$\text{TCD} = \left[ (L^* - L^*_{\text{b}})^2 + (a^* - a^*_{\text{b}})^2 + (b^* - b^*_{\text{b}})^2 \right]^{0.5} \quad (5)$$

wherein

L\*, a\*, and b\*: Film's color in the Hunter scale.

L\*<sub>b</sub>, a\*<sub>b</sub>, and b\*<sub>b</sub>: Background color in the Hunter scale.

WI: Whiteness index.

YI: Yellowness index.

TCD: Total color difference.

$$\text{Transparency} = \frac{\log(T_{600})}{t} \quad (6)$$

$$\alpha = \frac{1}{t} \ln \left( \frac{1}{T\%} \right) \quad (7)$$

wherein

T<sub>600</sub>: transmittance at 600 nm (%).

t: thickness of the film (mm).

α: absorption coefficient.

T%: transmittance.

$$\% \text{Radical scavenging} = \frac{(\text{Absorbance of control} - \text{Absorbance of sample})}{\text{Absorbance of control}} \times 100\% \quad (8)$$

Water absorption behavior was investigated by immersing pre-dried films in distilled water and measuring their weight after 5, 10, 15, 30, 60, 90, and 120 min. The %water absorption was calculated using Equation (9). The resulting absorption kinetics were fitted using 9 established mathematical models (Peleg, Singh, Gornicki, Pilosof, Czel and Czigany, Peppas, Vega-Galvez, Garcia-Pascual, and Weibull) with their respective Equations (10)–(18). Furthermore, fitness was evaluated using the coefficient of determination ( $R^2$ ) and root mean square error (RMSE), as defined in Equations (19) and (20), respectively.

$$\text{Water absorption(\%)} = \frac{\text{Water absorbed weight} - \text{Initial dried weight}}{\text{Initial dried weight}} \times 100 \quad (9)$$

$$\frac{t}{m_t} = K_2 t + K_1 \quad (10)$$

$$mr_t = a + \frac{b \times t}{c \times t + 1} \quad (11)$$

$$mr_t = a + b \times \left( 1 - \frac{1}{1 + b \times c \times t} \right) \quad (12)$$

$$mr_t = a + \frac{b \times t}{c + t} \quad (13)$$

$$mr_t = a \times t^m \quad (14)$$

$$\frac{mr_t/mr_\infty}{t^{1/2}} = K_1 t^{1/2} + K_2 \quad (15)$$

$$mr_t = a \times \exp \left[ -\frac{b}{(1+t)^\alpha} \right] \quad (16)$$

$$mr_t = 1 - \exp \left[ \left( -\frac{t}{a} \right)^b \right] \quad (17)$$

$$mr_t = m_e \times (m_o - m_e) \exp \left( \frac{-t}{\beta} \right)^\alpha \quad (18)$$

$$R^2 = 1 - \frac{\sum (y_i - \hat{y})^2}{\sum (y_i - \bar{y})^2} \quad (19)$$

$$\text{RMSE} = \sqrt{\frac{\sum (y_i - \hat{y})^2}{N}} \quad (20)$$

Herein

Equations (10)–(18) correspond to Peleg, Singh, Gornicki, Pilosof, Czel and Czigany, Peppas, Vega-Galvez, Garcia-Pascual, and Weibull models, respectively.

$m_t$ : moisture content (%) at time 't'.

$mr_t$ : moisture ratio at time 't'.

$mr_\infty$  and  $m_e$ : moisture ratio at 120 min.

$m$ : slope of curve fitting in Czel and Czigany model.

$K_1$  and  $K_2$ : intercept and slope of curve fitting in Peleg model, respectively.

$K_2$  and  $K_1$ : intercept and slope of curve fitting in Peppas model, respectively.

$a$ ,  $b$ ,  $c$ ,  $\alpha$ , and  $\beta$ : constants ( $\alpha = 0.9$ , a fixed value for Vega-Galvez's model only).

$R^2$ : coefficient of determination.

RMSE: root mean square error.

Mechanical properties of the films, including tensile strength (TS) and elongation at break (EB), were measured using a Texture Analyzer (Stable Micro Systems, TA-HD Plus, Serial No. 5529, Surrey, UK). Water vapor permeability (WVP) was determined by sealing film samples over jars containing anhydrous  $\text{CaSO}_4$  to maintain a relative humidity (RH) of 0%. The sealed jars were placed in a desiccator maintained at approximately 97% RH with a saturated  $\text{K}_2\text{SO}_4$  solution. The mass gain was monitored over an 8 h period, and WVP values were subsequently calculated. The TS, EB, and WVP were calculated using Equations (21), (22) and (23), respectively.

$$\text{TS (MPa)} = \frac{\text{Force used to break film (N)}}{\text{Film's surface area (mm}^2\text{)}} \quad (21)$$

$$\text{EB (\%)} = \frac{\text{Elongation at break (mm)}}{\text{Initial length (mm)}} \times 100 \quad (22)$$

$$\text{WVP} = \frac{\text{WVTR}}{P(R_1 - R_2)} \times t \quad (23)$$

wherein

P: saturation vapor pressure of water (Pa) at 25 °C,

$R_1$ : RH in the desiccator,

$R_2$ : RH in the cup,

t: film thickness (m).

The driving force [ $P(R_1 - R_2)$ ] in the experimental condition was calculated as 3073.93 Pa.

Biodegradability was evaluated by burying the films in soil (at 24% moisture), and the residual mass was measured every other day until 80% degradation was reached. The %weight loss was calculated as %biodegradation using Equation (24). The biodegradation data were analyzed by fitting first- and second-order kinetic models, utilizing Equations (25) and (26), respectively. The model fitness was assessed using the coefficient of determination ( $R^2$ ) and the root mean square error (RMSE) using Equations (19) and (20), respectively.

$$\% \text{biodegradation} = \frac{\text{Loss in film weight} \times 100}{\text{Initial weight}} \quad (24)$$

$$\text{Ln}(y) = mx + c \quad (25)$$

$$\text{Ln}(y) = a + bx + cx^2 \quad (26)$$

wherein

$\text{Ln}(y)$ : natural logarithm of %biodegradation.

x: biodegradation days.

m and c: slope and intercept, respectively, in Equation (25).

a, b, and c: constants in Equation (26).

Grapes were sorted for uniformity (shape, size, and color) and positioned in a glass jar with oat cellulose–resveratrol films and polystyrene (PS) film, covered and uncovered, at  $22 \pm 2$  °C and  $47 \pm 2$  % relative humidity. The weight loss, total soluble solids (TSS), pH, titratable acidity, and total ascorbic acid were measured. The percentage weight loss of the strawberries was determined from the change in fruit weight during storage (Equation (27)). Fruit total soluble solids (TSS) and pH were measured using a hand-held refractometer and a pH meter, respectively. Titratable acidity and total ascorbic acid were determined according to AOAC methods 942.15 and 967.21, respectively. For titratable acidity analysis, 100 mL of distilled water was transferred into a flask, followed by the addition of three drops of 1% phenolphthalein indicator. The solution was first titrated

with 0.1 N NaOH until a faint pink color appeared. Subsequently, 5 mL of strawberry juice was added, and the mixture was further titrated with 0.1 N NaOH until the faint pink endpoint was reached. Titratable acidity was then calculated using Equation (28). To quantify total ascorbic acid (vitamin C), the dye solution was prepared by dissolving 50 mg of 2,6-dichlorophenol indophenol and 42 mg of Na<sub>2</sub>CO<sub>3</sub> in 150 mL of hot distilled water, followed by adjusting the final volume to 200 mL. The dye was standardized by titrating 5 mL of a 0.1 mg/mL ascorbic acid standard solution mixed with 5 mL of 3% metaphosphoric acid (HPO<sub>3</sub>) until a faint pink color persisted for 15 s. The dye factor was subsequently determined using Equation (29). For sample analysis, 10 g of strawberry was homogenized with 3% HPO<sub>3</sub>, and the extract was adjusted to a final volume of 100 mL. After centrifugation, 5 mL of the supernatant was titrated with the standardized dye solution to the same pink endpoint. The total ascorbic acid content was then calculated using Equation (30).

$$\text{Weight loss(\%)} = \left( \frac{\text{Initial weight} - \text{After storage weight}}{\text{Initial weight}} \right) \times 100 \quad (27)$$

$$\text{Total titratable acidity (g/mL)} = \frac{V \times N \times EW \times 100}{1000 \times v} \quad (28)$$

wherein

V: Volume of NaOH used as titrant to get endpoint.

N: Normality of NaOH (0.1 N was used).

EW: Equivalent weight of dominating acid (citric acid).

v: Volume of sample.

$$\text{Dye factor} = \frac{\text{mg of ascorbic acid}}{\text{mL of Dye}} \quad (29)$$

$$\text{mg\% ascorbic acid} = \frac{\text{Titer} \times \text{Dye factor} \times \text{Vol. made up} \times 100}{\text{mL of aliquot} \times \text{g of sample taken}} \quad (30)$$

### 2.3. Statistical Analysis

Statistical analyses were conducted in RStudio (Version 2024.09.1+394) and Microsoft Excel for Mac (Version 16.88 (24081116)) with Solver Add-ins. Differences among film formulations were evaluated using Tukey's Honestly Significant Difference (HSD) test at  $p < 0.05$ . Water absorption and soil biodegradation kinetics were analyzed by nonlinear regression, and model performance was assessed using the coefficient of determination ( $R^2$ ) and root mean square error (RMSE).

## 3. Results and Discussion

### 3.1. Moisture Content and Water Solubility

The moisture content and water solubility of the films ranged from  $9.3 \pm 0.1$  to  $11.6 \pm 1.3\%$  and  $20.4 \pm 0.8$  to  $22.1 \pm 1.4\%$ , respectively (Table 1). No significant differences were observed among the formulations, indicating that resveratrol incorporation had little effect on the moisture affinity or solubility behavior of the films. Similar observations have been reported for polysaccharide-based films containing phenolic compounds, where the limited aqueous solubility and relatively hydrophobic nature of resveratrol restrict its interaction with the hydroxyl-rich cellulose matrix [49,53,54]. Consequently, the moisture-related properties remained primarily governed by the cellulosic network. The moisture content and water solubility values obtained in this study are comparable to those reported for grapevine and alfalfa cellulose films [52,55].

**Table 1.** Moisture content (MC, %), water solubility (WS, %), radical scavenging activity (RSA, %), and IC<sub>50</sub> (g/mL) of the film. The superscript letters indicate statistical groupings, using the same alphabet to denote statistically similar groups.

| Film    | MC                      | WS                      | RSA                       | IC <sub>50</sub>          |
|---------|-------------------------|-------------------------|---------------------------|---------------------------|
| OC-R0.0 | 11.0 ± 1.4 <sup>a</sup> | 21.6 ± 1.4 <sup>a</sup> | 4.05 ± 0.41 <sup>e</sup>  | 0.66 ± 0.02 <sup>a</sup>  |
| OC-R0.1 | 11.6 ± 1.3 <sup>a</sup> | 21.1 ± 1.1 <sup>a</sup> | 5.46 ± 0.26 <sup>d</sup>  | 0.53 ± 0.10 <sup>ab</sup> |
| OC-R0.3 | 10.5 ± 0.1 <sup>a</sup> | 20.4 ± 0.8 <sup>a</sup> | 13.76 ± 0.08 <sup>c</sup> | 0.41 ± 0.05 <sup>bc</sup> |
| OC-R0.5 | 9.3 ± 0.1 <sup>a</sup>  | 22.1 ± 1.4 <sup>a</sup> | 14.84 ± 0.04 <sup>b</sup> | 0.20 ± 0.01 <sup>cd</sup> |
| OC-R0.7 | 9.9 ± 0.7 <sup>a</sup>  | 21.2 ± 0.4 <sup>a</sup> | 19.70 ± 0.10 <sup>a</sup> | 0.12 ± 0.01 <sup>d</sup>  |

### 3.2. Color Properties

The films exhibited a light creamy-white appearance, as reflected by L\*, a\*, and b\* values ranging from 86.4 ± 1.6 to 88.6 ± 0.4, 0.2 ± 0.5 to 0.6 ± 0.4, and 2.1 ± 0.6 to 3.0 ± 0.7, respectively (Table 2). The high L\* values indicate a bright film surface, whereas the low a\* and b\* values indicate minimal red and yellow coloration. The slight cream coloration likely originated from residual non-cellulosic components retained during oat straw processing. Overall, resveratrol incorporation did not significantly affect the total color difference (2.4 ± 0.5–4.5 ± 1.3), yellowness index (3.4 ± 0.9–5.0 ± 1.2), and whiteness index (86.0 ± 1.6–88.4 ± 0.3). These results suggest that the resveratrol concentrations used in this study were insufficient to alter the visual appearance of the oat straw-derived cellulose films. The color characteristics were comparable to those reported for soyhull cellulose, alfalfa cellulose, soyhull cellulose–protein, soyhull cellulose–chitosan, alfalfa cellulose–starch, and alfalfa cellulose–carrageenan films [52,56–60].

**Table 2.** Oat cellulose–resveratrol (OC-R) film color in Hunter scale L\*, a\*, and b\*, total color difference (TCD), yellowness index (YI), and whiteness index (WI), and film transparency at 600 nm (Trans, %mm<sup>−1</sup>). The superscript letters indicate statistical groupings, using the same alphabet to denote statistically similar groups.

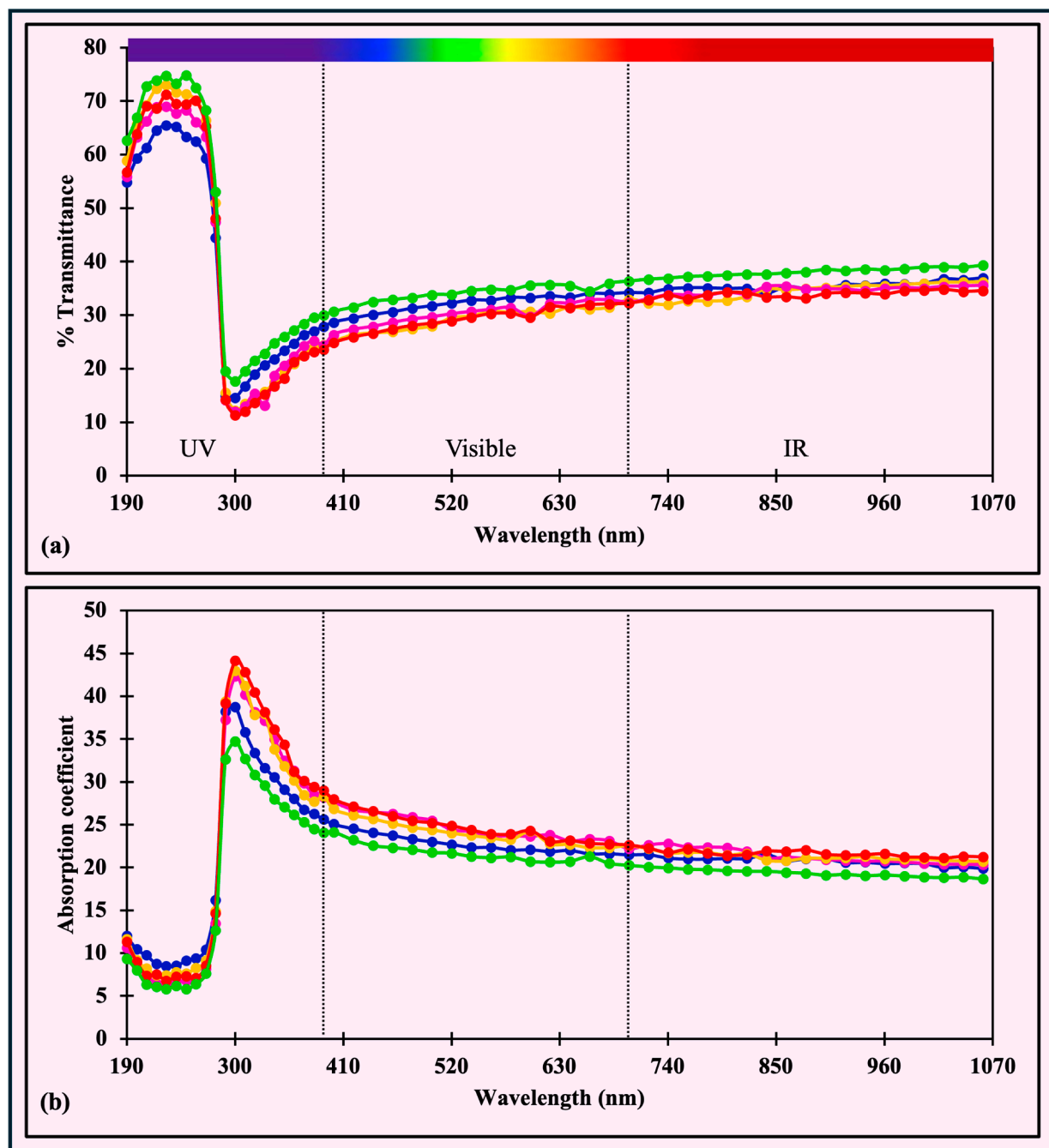
| Film    | L*                       | a*                     | b*                     | TCD                    | YI                     | WI                       | Trans                   |
|---------|--------------------------|------------------------|------------------------|------------------------|------------------------|--------------------------|-------------------------|
| OC-R0.0 | 86.6 ± 1.3 <sup>b</sup>  | 0.6 ± 0.4 <sup>a</sup> | 3.0 ± 0.7 <sup>a</sup> | 4.3 ± 1.3 <sup>a</sup> | 5.0 ± 1.2 <sup>a</sup> | 86.2 ± 1.4 <sup>b</sup>  | 31.0 ± 0.9 <sup>a</sup> |
| OC-R0.1 | 88.6 ± 0.4 <sup>a</sup>  | 0.2 ± 0.5 <sup>a</sup> | 2.1 ± 0.6 <sup>a</sup> | 2.4 ± 0.5 <sup>b</sup> | 3.4 ± 0.9 <sup>a</sup> | 88.4 ± 0.3 <sup>a</sup>  | 30.4 ± 1.1 <sup>a</sup> |
| OC-R0.3 | 88.4 ± 0.3 <sup>a</sup>  | 0.3 ± 0.3 <sup>a</sup> | 2.5 ± 0.5 <sup>a</sup> | 2.8 ± 0.4 <sup>b</sup> | 4.1 ± 0.7 <sup>a</sup> | 88.1 ± 0.2 <sup>a</sup>  | 29.7 ± 0.2 <sup>a</sup> |
| OC-R0.5 | 88.2 ± 0.4 <sup>ab</sup> | 0.3 ± 0.2 <sup>a</sup> | 2.7 ± 0.5 <sup>a</sup> | 3.0 ± 0.6 <sup>b</sup> | 4.4 ± 0.9 <sup>a</sup> | 87.9 ± 0.5 <sup>ab</sup> | 29.5 ± 0.5 <sup>a</sup> |
| OC-R0.7 | 86.4 ± 1.6 <sup>b</sup>  | 0.4 ± 0.4 <sup>a</sup> | 3.0 ± 0.3 <sup>a</sup> | 4.5 ± 1.3 <sup>a</sup> | 5.0 ± 0.6 <sup>a</sup> | 86.0 ± 1.6 <sup>b</sup>  | 29.4 ± 0.2 <sup>a</sup> |

### 3.3. Transparency, Electromagnetic Light Transmittance, and Absorption Coefficient

The films exhibited a slight decrease in transparency with increasing resveratrol concentration, from 31.0 ± 0.9 to 29.4 ± 0.2% mm<sup>−1</sup> (Table 2). The transparency values were lower than those reported for polypropylene (PP) films (38.2%) and higher than those of low-density polyethylene (LDPE) films (15–20%) [61], placing them within the range of conventional plastic packaging materials. Similar transparency values have been reported for corn cob cellulose [62], soyhull cellulose and lignocellulose [58,63], alfalfa cellulose [52], and alfalfa cellulose–carrageenan [56] films.

The films exhibited strong UV-Vis-IR light-blocking properties, which improved with increasing resveratrol concentration (Figure 1a). In the UVC region, the light transmittance of the control film was 62.7 ± 2.6% at 190 nm and increased to 72.6 ± 1.0% at 260 nm. The corresponding transmittance values for the resveratrol-containing films ranged from 54.9 ± 1.1 to 58.9 ± 3.5% at 190 nm and from 62.5 ± 1.3 to 70.2 ± 1.2% at 260 nm. A pronounced reduction in transmittance was observed in the UVB region, where values decreased to 19.6 ± 2.4%, 16.8 ± 2.2%, 13.5 ± 2.4%, 13.0 ± 2.9%, and 12.0 ± 3.1% at 310 nm

for the control, 0.1%, 0.3%, 0.5%, and 0.7% resveratrol films, respectively. In the UVA region, transmittance ranged from  $23.6 \pm 3.3$  to  $30.0 \pm 3.8\%$  at 390 nm. In comparison, transmittance remained relatively stable in the visible and infrared regions, reaching  $32.3 \pm 1.1$ – $36.4 \pm 2.8\%$  at 700 nm and  $34.6 \pm 1.2$ – $39.4 \pm 2.5\%$  at 1060 nm. The reduced transmission of ultraviolet radiation is advantageous for food packaging applications because UV exposure accelerates the degradation of vitamins, pigments, lipids, and other quality-related components during storage [64,65].



**Figure 1.** (a) Transmittance and (b) absorption coefficient of oat cellulose control film (Green), Oat cellulose–resveratrol 0.1% (Blue), Oat cellulose–resveratrol 0.3% (Yellow), Oat cellulose–resveratrol 0.5% (Pink), Oat cellulose–resveratrol 0.7% (Red).

The absorption coefficient profiles further support the enhanced light-blocking ability of the films (Figure 1b). In the UVC region, the absorption coefficient ranged from

$9.4 \pm 0.8$  to  $12.0 \pm 0.4$  at 190 nm and from  $6.4 \pm 0.3$  to  $9.4 \pm 0.4$  at 260 nm. A substantial increase in absorption was observed in the UVB region, where values reached  $32.7 \pm 2.4$ ,  $35.8 \pm 2.7$ ,  $40.2 \pm 3.5$ ,  $41.2 \pm 4.5$ , and  $42.8 \pm 5.1$  at 310 nm for the control, 0.1%, 0.3%, 0.5%, and 0.7% resveratrol films, respectively. In the UVA region, the absorption coefficient remained high, ranging from  $24.1 \pm 2.4$  to  $29.0 \pm 2.8$  at 390 nm. The values gradually decreased in the visible and infrared regions, reaching  $20.3 \pm 1.5$ – $22.6 \pm 0.7$  at 700 nm and  $18.7 \pm 1.2$ – $21.2 \pm 0.7$  at 1060 nm. The progressive increase in absorption with increasing resveratrol concentration is attributed to the conjugated aromatic structure of resveratrol. The stilbene chromophore present in resveratrol efficiently absorbs electromagnetic radiation, particularly in the ultraviolet region, thereby improving the light-shielding capability of the films [66]. Overall, resveratrol enhanced the UV-blocking performance of oat cellulose films while maintaining acceptable transparency, indicating its suitability as an active component for biodegradable food-packaging applications.

### 3.4. Antioxidant Property

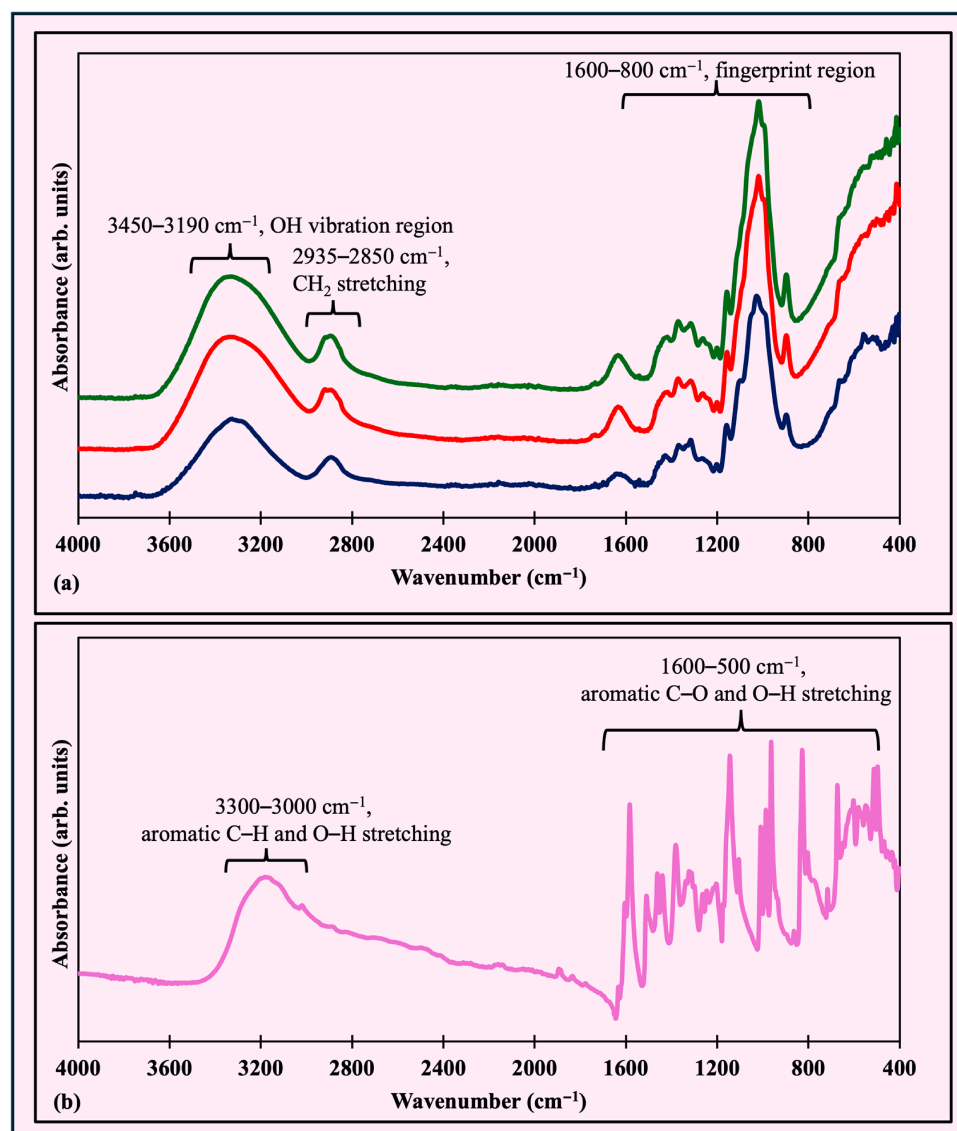
The incorporation of resveratrol markedly improved the antioxidant activity of the oat cellulose films (Table 1). The radical scavenging activity (RSA) increased from  $4.05 \pm 0.41\%$  in the control film to  $5.46 \pm 0.26\%$ ,  $13.76 \pm 0.08\%$ ,  $14.84 \pm 0.04\%$ , and  $19.70 \pm 0.10\%$  in 0.1%, 0.3%, 0.5%, and 0.7% resveratrol-added films, respectively. The increase in RSA demonstrates the contribution of resveratrol to the free-radical scavenging capacity of the films and confirms its effectiveness as an active antioxidant component. A corresponding decrease in  $IC_{50}$  was observed as resveratrol concentration increased. The control film exhibited an  $IC_{50}$  value of  $0.66 \pm 0.02$  g/mL, which decreased to  $0.53 \pm 0.10$ ,  $0.41 \pm 0.05$ ,  $0.20 \pm 0.01$ , and  $0.12 \pm 0.01$  g/mL for films containing 0.1%, 0.3%, 0.5%, and 0.7% resveratrol, respectively. The reduction in  $IC_{50}$  indicates that lower film concentrations were required to achieve 50% radical scavenging activity, further demonstrating enhanced antioxidant performance with increasing resveratrol content.

The observed behavior is attributed to the polyphenolic structure of resveratrol, which contains hydroxyl groups that can donate hydrogen atoms to neutralize free radicals and interrupt oxidative chain reactions [67]. Similar improvements in antioxidant activity have been reported following the incorporation of phenolic compounds into biopolymer films. Although carboxymethyl cellulose/sodium alginate films containing phycocyanin exhibited an RSA of 38.38% [68], the films containing 0.3–0.7% resveratrol displayed greater antioxidant activity than previously reported cellulose films derived from soyhull cellulose (5.5%) [58], soyhulls lignocellulose (10.9%) [63,69], corncob cellulose (15.1%) [62], alfalfa cellulose (7.3%) [52], alfalfa lignocellulose (5.9%) [70,71]. Enhanced antioxidant activity supports the potential application of resveratrol-loaded oat cellulose films as active packaging materials to reduce oxidative deterioration during food storage.

### 3.5. FTIR

In the FTIR spectra, several peaks in OC were retained or shifted in both OC and OC-R0.7% films. The retained peaks in the films from OC are 1735, 1700, 1542, 1535, 1508, and  $1428\text{ cm}^{-1}$ . Likewise, the peaks that shifted are from OC to OC and OC-R0.7% films are 3365–3250 to 3420–3200 and 3450–3190, 2910–2870 to 2935–2850 and 2935–2850, 1636 to 1635 and 1635, 1623 to 1624 and 1624, 1556 to 1555 and 1555, 1524 to 1525 and 1523, 1424 to 1423 and 1423, 1369 to 1372 and 1371, 1316 to 1317 and 1316, 1265 to 1263 and 1262, 1202 to 1201 and 1201, 1159 to 1157 and 1157, 1028 to 1019 and 1018, and 898 to 897 and  $897\text{ cm}^{-1}$ , respectively (Figure 2a). The peak at  $1463\text{ cm}^{-1}$  in OC shifted to  $1462\text{ cm}^{-1}$  in OC film but disappeared in OC-R0.7% film. Likewise, the peaks at 1651, 1608, 1456, 1361, 1334, and  $1099\text{ cm}^{-1}$  were present in OC, which disappeared in both films. The new peaks at 1418

and  $996\text{ cm}^{-1}$  were present in both films, while the peak at  $849\text{ cm}^{-1}$  was present in the OC-R0.7% film only.



**Figure 2.** The FTIR spectra of (a) oat cellulose (OC) (blue line), OC film (red line), and OC-R0.7% film (resveratrol 0.7% added to OC) (green line), and (b) pure resveratrol (purple line).

The peak at  $898\text{ cm}^{-1}$  refers to the  $\beta$ -glycosidic linkage of cellulose's glucose ring [72,73]. The bands at 3365–3250, 2910–2870, 1608, and  $1028\text{ cm}^{-1}$  refer to  $-\text{OH}$  vibration,  $\text{C}_3\text{OH}\cdots\text{O}_5$  intra-chain,  $\text{C}_3\text{OH}\cdots\text{OC}_6$  inter-chain, and  $\text{C}_6\text{O}\cdots\text{OH}$  intra-chain hydrogen bonding interactions [74],  $\text{CH}_2$  asymmetrical and symmetrical stretching [74],  $\text{CO}$  vibration [55], and  $\text{C}=\text{O}$  stretching [74,75], respectively, and are associated with the mannan group [76]. Likewise, 1556, 1542, 1535, 1524, 1508, 1463, 1456, 1428, 1424, 1369, 1361, 1334, 1316, 1265, 1202, 1159, and  $1099\text{ cm}^{-1}$  peaks demonstrate the presence of xylan groups [77]. The 1735 and  $1700\text{ cm}^{-1}$  peaks showed the presence of a  $-\text{C}=\text{O}$  carbonyl group [78], while 1651, 1636, and  $1623\text{ cm}^{-1}$  peaks are associated with bound water. The peaks at  $1369\text{ cm}^{-1}$  to  $\text{C}-\text{H}$  oscillation [79],  $1361\text{ cm}^{-1}$  to xyloglucan [80],  $1316\text{ cm}^{-1}$  to  $\text{O}-\text{H}$  bending [81,82],  $1265\text{ cm}^{-1}$  to  $\text{CH}_2$  deformation [75], 1202, 1159, and  $1099\text{ cm}^{-1}$  correspond to  $\text{C}-\text{O}-\text{C}$  vibration and  $\text{CH}_2$  rocking [73,83], and the rest of the peaks within 1556–1334  $\text{cm}^{-1}$  attribute to  $\text{C}-\text{H}$  bond [78].

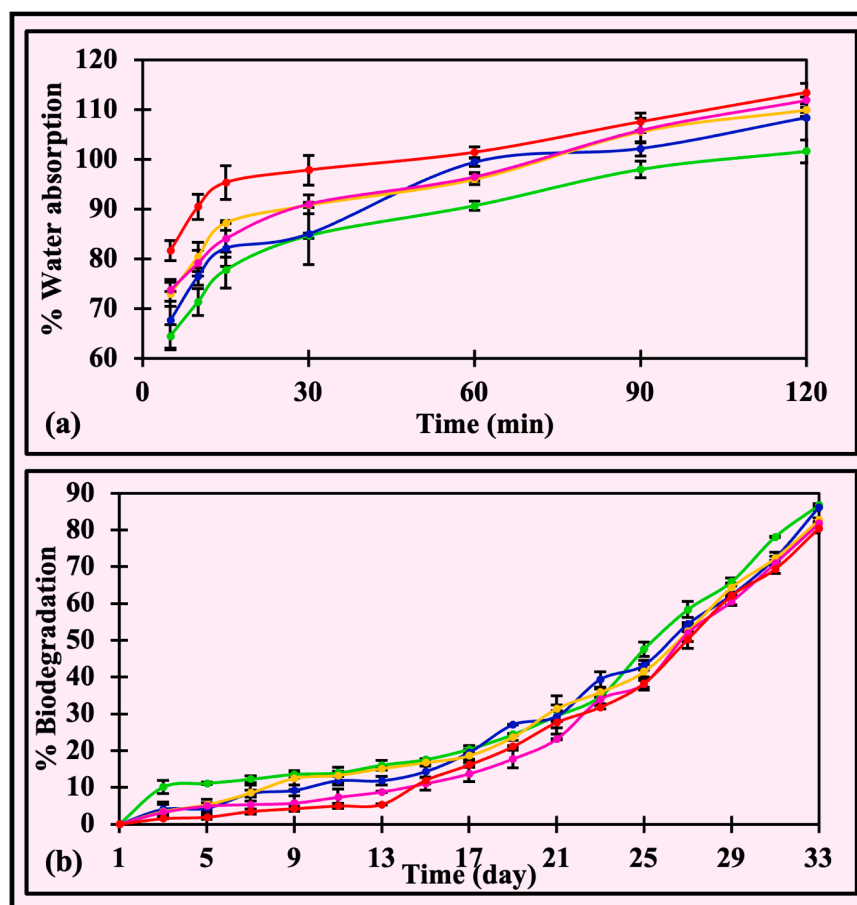
The new peaks at 1418 and  $996\text{ cm}^{-1}$  were observed in both films, indicating the formation of interactions among cellulose, zinc chloride, calcium chloride, and glycerol.

Likewise, a new peak at  $849\text{ cm}^{-1}$  appeared in the OC-R0.7% film, providing evidence of aromatic C–H out-of-plane and C–C bending with aromatic ring deformation [84,85]. Resveratrol exhibited two broad fingerprint regions at  $3000\text{--}3300\text{ cm}^{-1}$  and  $1600\text{--}500\text{ cm}^{-1}$  (Figure 2b). Within these regions,  $3300\text{ to }3200\text{ cm}^{-1}$ ,  $3200\text{ to }3100\text{ cm}^{-1}$ , and  $3100\text{ to }3000\text{ cm}^{-1}$  correspond to phenolic O–H stretching, shifting of C–H stretching to O–H stretching, and aromatic C–H stretching, respectively [86]. The bands at  $1600\text{--}1400\text{ cm}^{-1}$  represent aromatic C=C stretching [87,88],  $1400\text{ to }1100\text{ cm}^{-1}$  for C–O stretching and O–H stretching [89], and  $900\text{--}500\text{ cm}^{-1}$  for out-of-plane aromatic bending [88]. The peaks at and around  $965\text{ cm}^{-1}$  correspond to the trans-conformation C–H bend and are used in the raw resveratrol purity test [90]. The broader range of overlaps is present in the resveratrol peak with oat cellulose.

Overall peak intensification was observed in the OC-R0.7% film compared with the control film. This increase may be attributed to the incorporation of resveratrol, which overlaps with the aromatic vibrational bands of cellulose and residual xylan and mannan present in the oat-cellulose matrix.

### 3.6. Water Absorption and Kinetics

The water absorption capacity of the films increased with resveratrol incorporation (Figure 3a). After 120 min, the control film exhibited water absorption of  $101.7 \pm 2.3\%$ , which increased to  $108.4 \pm 0.3\%$ ,  $110.0 \pm 0.5\%$ ,  $111.9 \pm 0.7\%$ , and  $113.4 \pm 1.9\%$  for films containing 0.1%, 0.3%, 0.5%, and 0.7% resveratrol, respectively. The slight increase in water uptake may be attributed to the hydroxyl groups present in resveratrol, which can promote interactions with water molecules and facilitate moisture absorption within the film matrix [91].



**Figure 3.** (a) Water absorption and (b) biodegradation of oat cellulose control film (Green), Oat cellulose–resveratrol 0.1% (Blue), Oat cellulose–resveratrol 0.3% (Yellow), Oat cellulose–resveratrol 0.5% (Pink), Oat cellulose–resveratrol 0.7% (Red).

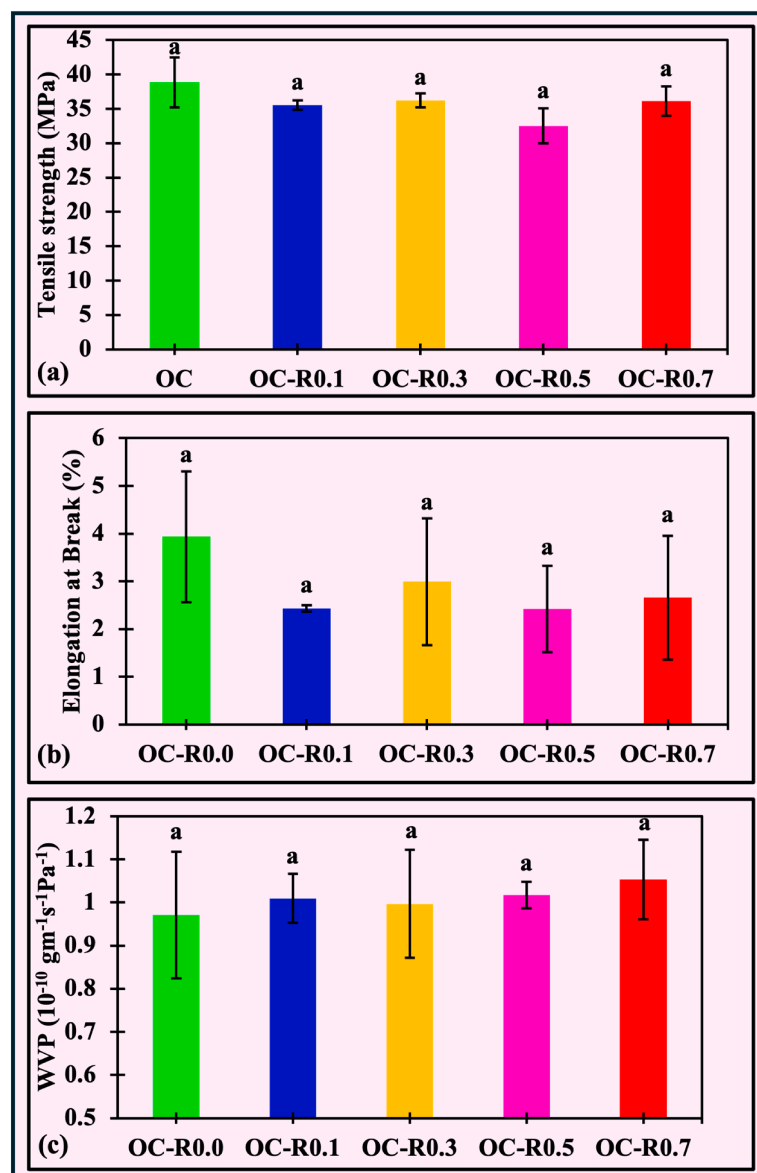
Water absorption behavior was evaluated using nine mathematical models, and model performance was assessed using the coefficient of determination ( $R^2$ ) and root mean square error (RMSE) (Table S1). Among the evaluated models, the Singh, Pilosof, Gornicki, and Czel and Czigány models provided acceptable fits, with  $R^2$  values ranging from 0.9309 to 0.9936. However, the Peleg model produced the highest  $R^2$  values (0.9954–0.9977) and the lowest RMSE values (0.0187–0.0244), indicating superior agreement with the experimental data. Consequently, the Peleg model was selected to describe the water absorption behavior of the films. The Peleg rate constant ( $K_1$ ) and capacity constant ( $K_2$ ) ranged from 0.0320–0.0514 and 0.0088–0.0096, respectively. The  $K_1$  parameter is inversely related to the initial water absorption rate, whereas  $K_2$  is inversely related to the equilibrium water absorption capacity. The relatively low  $K_1$  and  $K_2$  values indicate rapid water uptake and a high water-absorption capacity by the cellulose-based films. Similar observations have been reported for films derived from microcrystalline cellulose [92], soyhull lignocellulose [58,63,69], corncob cellulose [62], switchgrass lignocellulose [93], alfalfa lignocellulose [52,70,71], and spent coffee ground lignocellulose [94].

### 3.7. Mechanical Properties

The films exhibited relatively high tensile strength with limited flexibility. Tensile strength (TS) and elongation at break (EB) ranged from  $32.5 \pm 2.5$  to  $38.9 \pm 3.6$  MPa and  $2.4 \pm 0.9$  to  $3.9 \pm 1.4\%$ , respectively (Figure 4a,b). The incorporation of resveratrol did not significantly affect either TS or EB, indicating that the mechanical integrity of the cellulose– $\text{CaCl}_2$  network was largely preserved. Although not statistically significant, a slight decrease in both TS and EB was observed as the resveratrol concentration increased. This behavior may be associated with resveratrol's distribution within the hydrophilic cellulose matrix, which could partially interfere with intermolecular hydrogen bonding and reduce the efficiency of stress transfer. However, the magnitude of these changes was insufficient to alter the films' overall mechanical performance. The results suggest that the cellulose– $\text{CaCl}_2$  network remained structurally stable after resveratrol incorporation and retained its ability to provide mechanical strength while accommodating the active component. Similar mechanical behavior has been reported in cellulose-based films containing phenolic additives, in which the bioactive compound contributed functional properties without substantially altering the matrix's mechanical characteristics [95].

### 3.8. Water Barrier Property

Water vapor permeability (WVP) is an important packaging property because it governs moisture transfer between food and the surrounding environment, thereby influencing product quality and shelf life. The incorporation of resveratrol resulted in a slight increase in WVP (expressed as  $\times 10^{-10} \text{ g}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$ ) from  $0.97 \pm 0.15$  in the control film to  $1.01 \pm 0.06$ ,  $1.00 \pm 0.13$ ,  $1.02 \pm 0.03$ , and  $1.05 \pm 0.09$  in films containing 0.1%, 0.3%, 0.5%, and 0.7% resveratrol, respectively (Figure 4c). The modest increase in WVP may be linked to the hydroxyl groups in resveratrol, which can promote moisture sorption and facilitate water vapor diffusion through the film matrix [91]. However, the overall changes were small, indicating that resveratrol incorporation had a limited effect on the moisture barrier performance of the cellulose films. The WVP values obtained in this study are comparable to those reported for bacterial cellulose–chitosan films containing grape bagasse antioxidant extract (0.31–0.93) [96] and other cellulose-based films derived from soyhulls [58,63,69], alfalfa [52,70,71], cow dung [97], grapevine [55], and spent coffee grounds [94]. These results indicate that incorporating resveratrol improved the films' functional activity while maintaining their water-vapor barrier properties.



**Figure 4.** (a) Tensile strength, (b) elongation at break, and (c) water vapor permeability (WVP) of oat cellulose control film (Green), Oat cellulose–resveratrol 0.1% (Blue), Oat cellulose–resveratrol 0.3% (Yellow), Oat cellulose–resveratrol 0.5% (Pink), Oat cellulose–resveratrol 0.7% (Red). The letter ‘a’ in the bar graph indicates that there was no statistically significant difference between the samples.

### 3.9. Soil Biodegradation

All films exhibited rapid biodegradation under soil burial conditions, with more than 80% weight loss observed within 33 days (Figure 3b). The control film exhibited the greatest degradation, with a weight loss of  $86.72 \pm 0.50\%$  after 33 days. Incorporation of resveratrol resulted in a slight reduction in biodegradation, with final weight losses of  $86.16 \pm 0.82\%$ ,  $82.71 \pm 0.51\%$ ,  $81.72 \pm 0.60\%$ , and  $80.44 \pm 1.23\%$  for films containing 0.1%, 0.3%, 0.5%, and 0.7% resveratrol, respectively. Although biodegradation decreased with increasing resveratrol concentration, all formulations retained a high degree of degradability throughout the study period. Similar biodegradation behavior has been reported for other active biodegradable films. For example, starch/nanocellulose films containing *Amaranthus viridis* extract exhibited more than 80% weight loss within 15 days [98], while cellulose-based active films containing epigallocatechin-3-gallate underwent complete biodegradation within 21 days [99]. The rapid degradation observed in the present study confirms that incorporating resveratrol did not compromise the biodegradable nature of the cellulose matrix.

The biodegradation behavior was further evaluated using first- and second-order reduction reaction kinetics. The first-order model produced  $R^2$  and RMSE values of 0.9425–0.9814 and 0.0936–0.1920, respectively (Table S2). In comparison, the second-order model yielded higher  $R^2$  values (0.9802–0.9924) and lower RMSE values (0.0621–0.1305), indicating a superior fit to the experimental data. Therefore, the biodegradation of the oat straw-derived cellulose films was best described by second-order reaction kinetics. The calculated half-life values ranged from 26.4 to 27.8 days, suggesting that resveratrol incorporation had only a minor influence on the degradation rate. The second-order biodegradation pattern has also been reported for films prepared from soyhull cellulose [58], soyhulls lignocellulose [63,69], corncob cellulose [62], alfalfa cellulose [52], alfalfa lignocellulose [70,71], and grapevine cellulose [55]. The rapid biodegradation and relatively short half-life observed in this study support the suitability of oat cellulose–resveratrol films as environmentally compatible packaging materials that provide active functionality while maintaining end-of-life degradability.

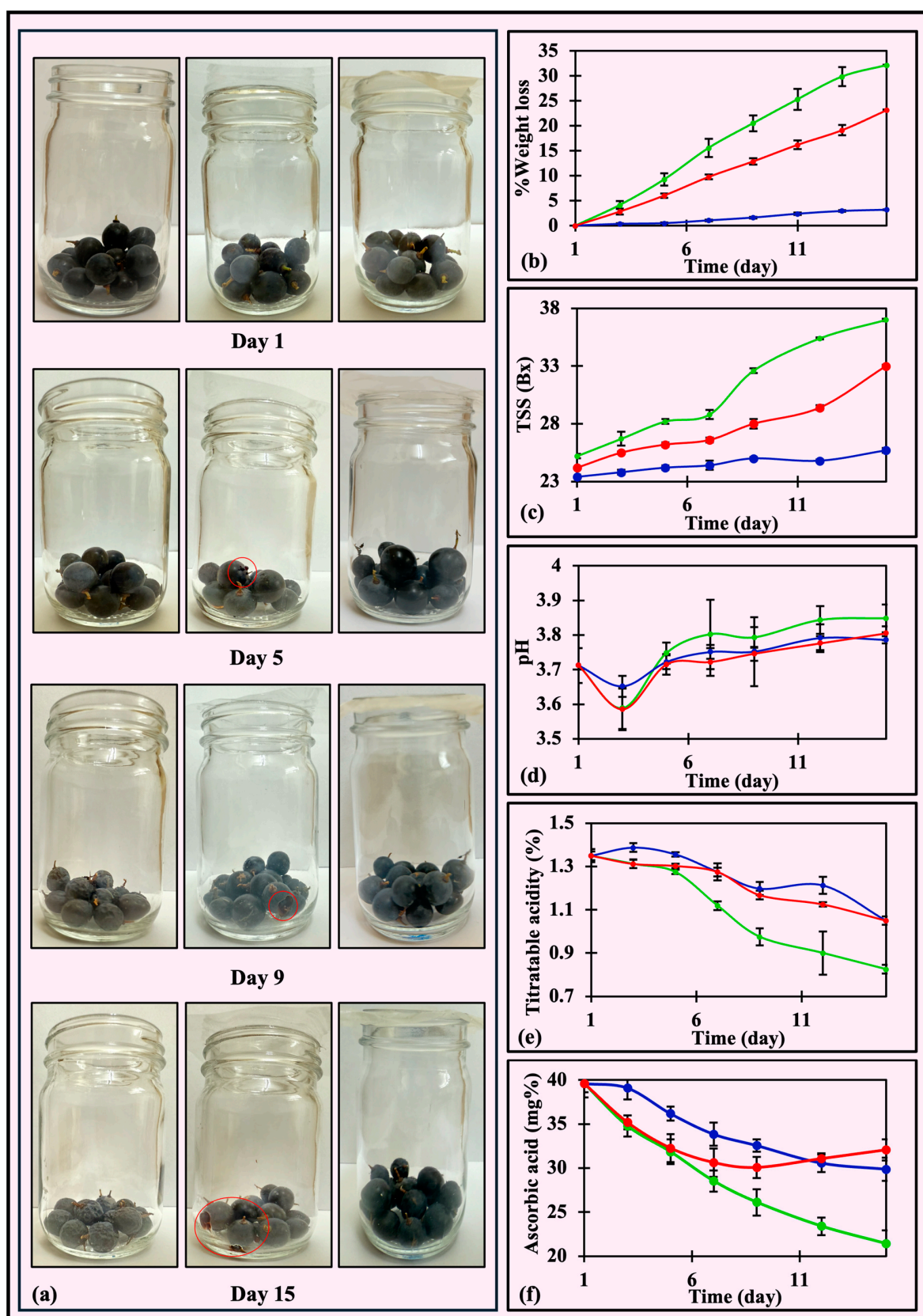
### 3.10. Fruit Stability Test

The fruit preservation experiment was designed to determine whether the functional properties measured for the oat cellulose–resveratrol films translated into improved storage performance of fresh grapes. Specifically, antioxidant activity, ultraviolet light shielding, and gas permeability were expected to reduce oxidative deterioration while maintaining an atmosphere favorable for fruit quality during storage.

Grapes were stored in glass jars covered with OC-R0.7% film, polystyrene (PS) film, or left uncovered (Figure 5a). During storage, gas accumulation was observed in the PS-covered jars starting on day 3. Grapes enclosed in PS film began to burst on day 5, and visible mold growth appeared by day 7. In contrast, grapes covered with OC-R0.7% film and those left uncovered remained free of visible mold growth throughout the 15-day storage period. No visible mold growth was observed in grapes covered with the oat cellulose–resveratrol film during the storage period. However, the microbial populations were not quantified; this observation cannot be conclusively attributed to antimicrobial activity.

Weight loss increased throughout storage across all treatments (Figure 5b). Grapes covered with PS film had the lowest weight loss ( $3.2 \pm 0.1\%$ ), whereas OC-R0.7% film-covered and uncovered grapes had weight losses of  $23.2 \pm 0.1\%$  and  $32.1 \pm 0.1\%$ , respectively. Fresh fruits continuously respire and transpire during storage, leading to moisture loss and a gradual reduction in mass [100–102]. The low permeability of PS restricted gas exchange, contributing to carbon dioxide accumulation and subsequent fruit deterioration. In contrast, the OC-R0.7% film allowed moisture loss while maintaining adequate gas exchange, preventing fruit bursting and preserving overall fruit integrity. Uncovered grapes experienced the greatest moisture loss and progressively dehydrated toward raisin formation.

Total soluble solids (TSS) increased during storage across all treatments (Figure 5c), reflecting moisture loss and the conversion of carbohydrates and pectic substances into soluble sugars [103]. TSS rose from  $23.4 \pm 0.2$  to  $25.7 \pm 0.2$  °Bx in PS-covered grapes and from  $24.2 \pm 0.1$  to  $33.0 \pm 0.1$  °Bx in OC-R0.7% film-covered grapes between days 1 and 15. In uncovered grapes, TSS increased from  $25.2 \pm 0.2$  to  $35.4 \pm 0.1$  °Bx by day 12, and the day 15 value exceeded the refractometer's measurement range. The slower TSS increase in OC-R0.7% film-covered grapes compared with uncovered grapes indicates a reduced rate of compositional changes associated with fruit ripening and dehydration. Only minor changes in pH were observed during storage (Figure 5d). The pH increased from  $3.712 \pm 0.050$  to  $3.786 \pm 0.010$ ,  $3.805 \pm 0.020$ , and  $3.848 \pm 0.040$  in PS-covered, OC-R0.7% film-covered, and uncovered grapes, respectively. These small variations suggest that pH was not a major factor in differences in fruit quality among the storage treatments.



**Figure 5.** The observations (a) grapes in the glass jars (left to right: uncovered, polystyrene film covered, and Oat cellulose–resveratrol 0.7% film covered). Red circle shows the defects in the grapes, (b) %Weight loss, (c) total soluble solids (TSS), (d) pH, (e) %titratable acidity (%TA), and (f) total ascorbic acid (TAA) of grapes during storage in a glass jar, polystyrene-covered (Red), Oat cellulose–resveratrol 0.7% (Green), and uncovered (Blue).

Titrateable acidity gradually decreased throughout storage (Figure 5e), declining from  $1.4 \pm 0.03\%$  to  $1.1 \pm 0.02\%$ ,  $1.1 \pm 0.02\%$ , and  $0.8 \pm 0.02\%$  in PS-covered, OC-R0.7% film-covered, and uncovered grapes, respectively. The reduction in titrateable acidity reflects the continued utilization of organic acids during ripening and storage [52,104]. The greater retention of acidity in grapes covered with the OC-R0.7% film compared with uncovered grapes suggests a slower progression of ripening-related changes.

The total ascorbic acid content decreased across all treatments during storage (Figure 5f). Values declined from  $39.6 \pm 1.6$  mg% to  $29.9 \pm 1.3$ ,  $32.1 \pm 1.2$ , and  $21.4 \pm 1.5$  mg% in PS-covered, OC-R0.7% film-covered, and uncovered grapes, respectively. The reduction in ascorbic acid is associated with oxidative degradation and endogenous metabolic activity during storage [105]. Grapes covered with the OC-R0.7% film retained the highest ascorbic acid content among the treatments, which is consistent with the enhanced antioxidant activity of the resveratrol-containing films, which likely reduced oxidative degradation during storage.

Collectively, the preservation results are consistent with the functional characteristics measured for the films. The enhanced antioxidant activity of the resveratrol-containing films likely reduced oxidative degradation of quality-related compounds such as ascorbic acid during storage. In addition, improved ultraviolet light-blocking properties may limit photooxidative reactions that accelerate pigment and nutrient degradation. Unlike polystyrene, the cellulose-based film also allowed sufficient gas exchange to avoid excessive carbon dioxide accumulation while still reducing moisture loss compared with uncovered fruit. These complementary functions provide a mechanistic explanation for the improved preservation of grape quality observed during storage.

### 3.11. Functional Rationale for Grape Preservation

The suitability of the oat cellulose–resveratrol films for grape preservation is supported by the relationships between the measured film properties and the physiological processes governing postharvest grape quality. Grapes continue to respire after harvest and are susceptible to moisture loss, oxidative degradation, nutrient loss, and ultraviolet-induced deterioration. Therefore, effective packaging should balance gas permeability, moisture regulation, and protection against oxidative damage.

The films developed in this study exhibited several characteristics that address these requirements. Resveratrol significantly enhanced antioxidant activity, potentially helping protect oxidation-sensitive constituents such as ascorbic acid. The films also showed improved ultraviolet light-blocking ability, reducing the potential for photooxidative deterioration during storage. At the same time, incorporating resveratrol caused only minor changes in water-vapor permeability and mechanical properties, indicating that the films retained the transport characteristics necessary to maintain an appropriate storage atmosphere. The fruit preservation experiment demonstrated reduced changes in weight loss, soluble solids, titrateable acidity, and ascorbic acid compared with uncovered fruit, consistent with these measured functional properties.

Taken together, enhanced antioxidant activity, ultraviolet light shielding, controlled water vapor transfer, and appropriate gas exchange are likely to function synergistically to reduce oxidative deterioration while maintaining the physiological quality of grapes during storage. Although antimicrobial activity was not evaluated in the present study, the observed preservation performance demonstrates that antioxidant protection, ultraviolet shielding, and appropriate gas exchange together provide a scientifically supported rationale for using these biodegradable films for grape packaging.

## 4. Conclusions

The growing demand for sustainable food packaging has accelerated the search for renewable alternatives to conventional synthetic materials. In this study, biodegradable, antioxidant active packaging films were developed from oat straw-derived cellulose and resveratrol. Resveratrol significantly enhanced the films' antioxidant activity and ultraviolet light-blocking properties while causing only minor changes in moisture content, water solubility, mechanical properties, water vapor permeability, and biodegradation behavior. During grape storage, the films maintained fruit quality by moderating changes in weight loss, total soluble solids, titratable acidity, and ascorbic acid content, while providing sufficient gas exchange to prevent the excessive carbon dioxide accumulation observed in polystyrene-covered grapes. These findings support the potential of oat straw-derived cellulose films containing resveratrol as multifunctional, biodegradable packaging materials for fresh-produce applications. The preservation performance observed during grape storage is best explained by the combined effects of enhanced antioxidant activity, improved ultraviolet light shielding, balanced moisture transfer, and sufficient gas exchange, rather than by a single preservation mechanism. These results demonstrate that effective preservation can be achieved through the combined action of multiple functional packaging properties without requiring attribution to a single preservation mechanism. Future studies should investigate antimicrobial activity, resveratrol release kinetics, and film microstructure further to clarify the relative contributions of each preservation mechanism.

**Supplementary Materials:** The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/app16157409/s1>: Table S1. Water absorption kinetic model fittings; Table S2. Soil biodegradation kinetic model fitting (HL represents film's half-life).

**Author Contributions:** Conceptualization, S.J.; methodology, S.R., K.R., S.P. and S.J.; software, S.R. and S.P.; validation, S.R. and S.P.; formal analysis, S.R., K.R. and S.P.; investigation, S.R., K.R. and S.P.; resources, S.J.; data curation, S.R., K.R. and S.P.; writing—original draft preparation, S.R., K.R. and S.P.; writing—review and editing, S.R., S.P. and S.J.; visualization, S.R. and S.P.; supervision, S.J.; project administration, S.J.; funding acquisition, S.J. All authors have read and agreed to the published version of the manuscript.

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