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Original article

INVESTIGATION OF DRYING KINETICS AND QUALITY CHARACTERISTICS OF FRUIT BARS ENRICHED WITH *CHLORELLA* AND *SPIRULINA PLATENSIS*

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ABSTRACT:

The aim: This study analyzes the drying kinetics and the influence of technological parameters on the quality of functional fruit bars enriched with the microalgae *Spirulina platensis* and *Chlorella*. The aim is to optimize the conditions for convective drying while preserving the sensory properties of the final product.

Materials and methods: The researchers investigated two independent variables: drying temperature (60–70°C) and fruit layer thickness (9–15 mm). The dynamics of moisture content change were monitored by recording drying curves. The degree of deformation of the fruit bars after drying was calculated as the ratio between the initial and final thickness of the samples.

Results: A drying temperature of approximately 65°C and a layer thickness of 9–12 mm yielded optimal conditions for a high sensory score (>9.0) and low deformation (<5.0 mm). The results confirm the applicability of a modeling approach for designing technological regimes for the production of sustainable, functional fruit-based products with high nutritional value.

Conclusion: The tasting evaluation shows that the highest ratings (over 9) were for bars with a thickness of 9 mm and a drying temperature of 60°C and 65°C, respectively, and a deformation of 4.3 and 5.6 mm, respectively. Bars with a thickness of 12 mm, dried at 60°C, had a slightly lower tasting evaluation (8.6), but their deformation was significant at 6.3 mm.

Keywords: convective drying, fruit bars, *Spirulina*, *Chlorella*, drying kinetics, sensory evaluation, regression models,

INTRODUCTION:

In recent years, there has been growing interest in fruit bars enriched with superfoods as an eco-friendly, health-promoting snack that provides a rapid energy boost. Studies on high-protein bars have shown that adults often deem them unsuitable for children because of their high caloric density [1]. As a result, research is increasingly shifting toward fruit-based bars fortified with various superfoods. Fruits naturally supply sugars, vitamins, and other nutrients [2] and are generally more palatable to children [3].

Prunes are especially attractive for such formulations: their high levels of free amino acids, natural sugars, and polyphenols make them a valuable functional ingredient. However, their moisture content exceeds 80 %, so the drying process must be optimized to achieve the target water activity and texture [4]. The drying kinetics of plum derivatives have been examined in both tunnel and laboratory dryers, and product quality attributes such as color, phenolic retention, and water activity are strongly temperature-dependent [5].

Incorporating *Spirulina platensis* or *Chlorella vulgaris* into fruit bars further boosts the protein content, essential fatty acids, and specific antioxidants such as phycocyanin and lutein [6]. Acceptable sensory quality has been reported with micro-alga additions up to 2 % in fruit or cereal bars; higher levels impart an intense green hue and aftertaste. Other studies show that in 3D-printed fruit bars containing Chlorella, structural integrity is maintained up to 3 % inclusion [7]. Adding these microalgae to prune-based matrices increases the protein level and raises the water-binding capacity and viscosity [8]. These changes can prolong the falling-rate period of drying and demand adjustments to the thermal regime to prevent surface hardening and internal moisture gradients [9].

Objectives of the present study

- **To characterize the thin-layer drying kinetics** of fruit bars produced from prune purée enriched with *Spirulina platensis* or *Chlorella vulgaris*.
- **The aim is to use multifactor regression to model the relationships** among drying temperature, layer thickness, and quality parameters (dimensional shrinkage, sensory evaluation), with the aim of establishing optimal industrial conditions for producing sustainable, nutritionally rich snack bars.

MATERIALS AND METHODS:

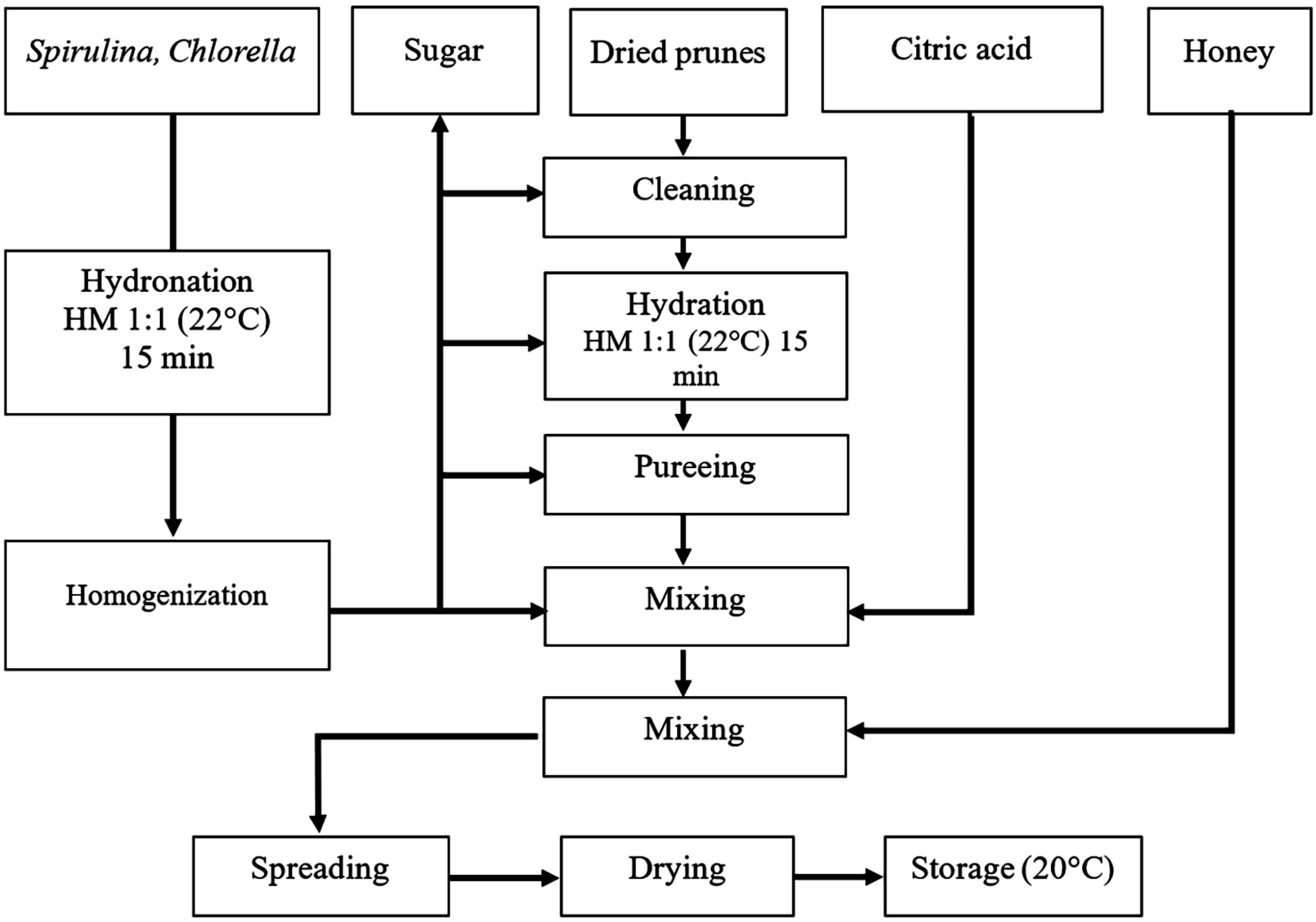
Sample preparations

Prune-based fruit bars were developed with the addition of 3 % freshwater microalgae (*Chlorella vulgaris* and *Spirulina platensis*). The manufacturing process and the formulation are presented in Figure 1 and Table 1, respectively. The fruit purée was spread to layer thicknesses of 9, 12 and 15 mm and dried at 60, 65 and 70°C.

Table 1. Formulation of fruit bars with freshwater microalgae

	Ingridients, %	Plum purée, %	Sugar, %	Honey, %	Citric acid, %
Spirulina platensis	3	71.85	22	3	0.15
Chlorella vulgaris	3	71.85	22	3	0.15

Fig. 1. Technological flow diagram for producing prune-based fruit bars enriched with convectively dried *Chlorella vulgaris* and *Spirulina platensis*



Determination of active acidity

The active acidity (pH) of the test samples was determined in accordance with BDS ISO 4316:1994 [10], using a potentiometric method with a HANNA HI1230B pH meter.

Investigation the drying kinetics

The drying rate constant was determined from the equation of the drying curve:

$$-\frac{dU^C}{d\tau} = K^C(U^C - U_P^C)$$

Where U_P^C – *equilibrium moisture content*, %

U^C - current moisture content, %

K^C - drying rate constant, min^{-1}

Determination of the degree of deformation

The degree of deformation (shrinkage) was calculated using the Equation:

D = 100.a/b, where

D – degree of deformation, %

a – thickness of the sample after drying, mm

b – thickness of the sample before drying, mm

RESULTS:

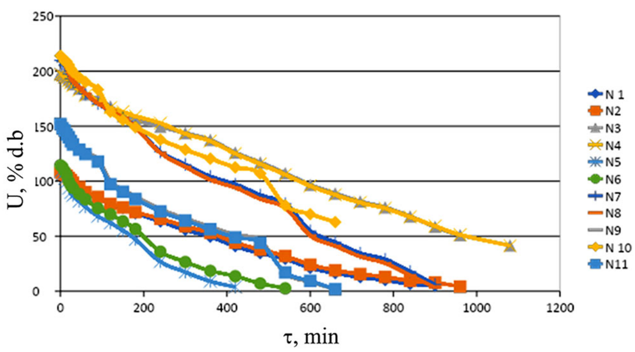
Based on the preliminary investigations, the main independent variables affecting the drying kinetics were identified as:

- **X_1 – drying-air temperature, *t* (°C);**
- **X_2 – drying-layer thickness (tray loading), *b* (mm).**

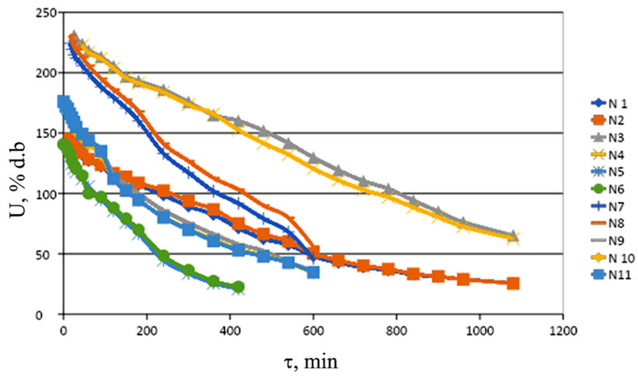
Figure 2a and b display the drying curves, U = f(τ), for fruit bars enriched with *Chlorella vulgaris* and *Spirulina platensis*. Depending on the drying-air temperature and tray loading, the drying time for both formulations ranges from 7.0 to 18.0 hours.

Fig. 2. Drying curves of fruit bars

a) for *Chlorella vulgaris*



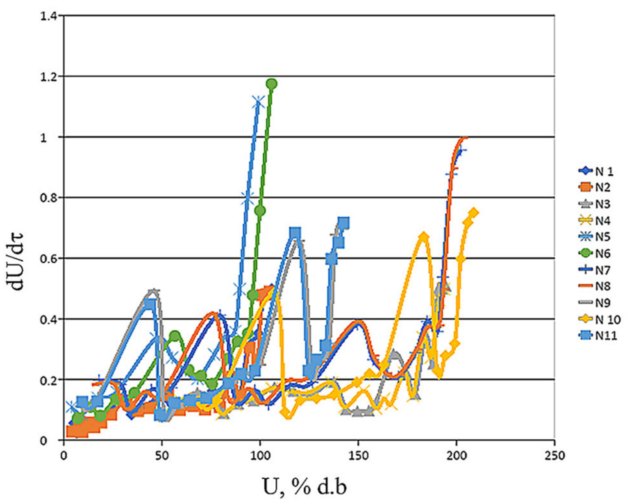
***b*)** *for Spirulina Platensis*



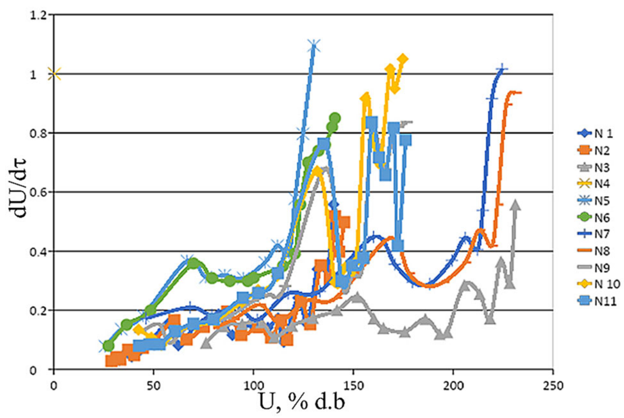
Drying-rate curves were obtained as a function of the moisture content of the fruit bars. The results are shown in Figure 3.

Fig. 3. Drying-rate curves of fruit bars.

a) for *Chlorella vulgaris*



***b*)** *for Spirulina Platensis*



A study was carried out to evaluate how the drying parameters influence both the degree of deformation and the drying-rate constants of the fruit bars. The results are presented on Figures 4 and 5.

Fig. 4. Influence of drying parameters on the drying-rate constants of fruit bars

a) for *Chlorella vulgaris* *__b__) for Spirulina Platensis*

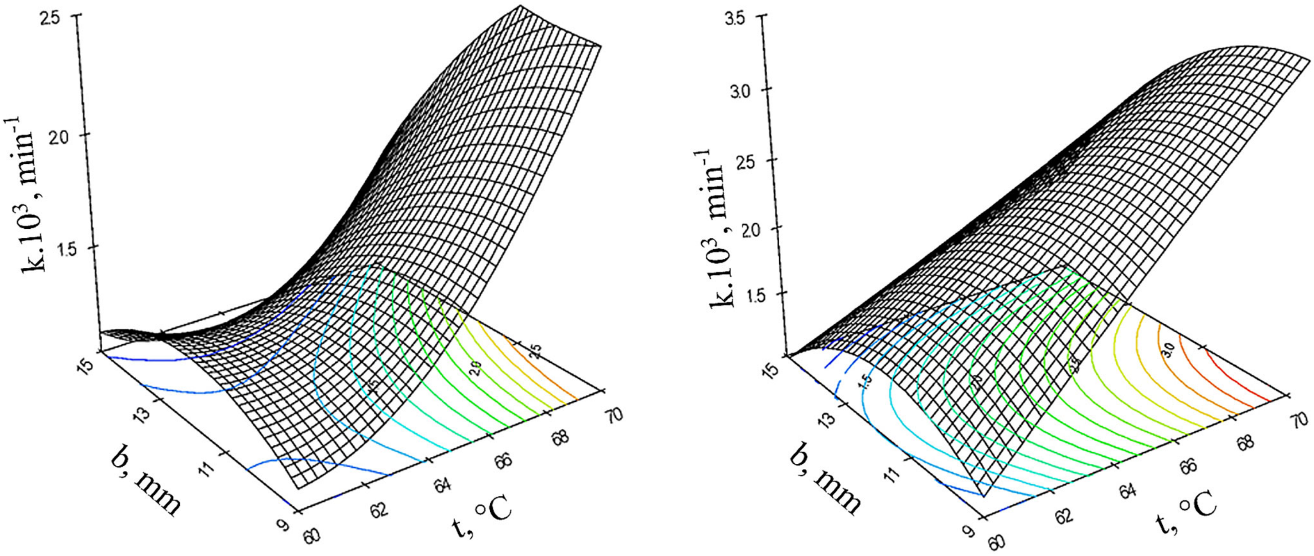
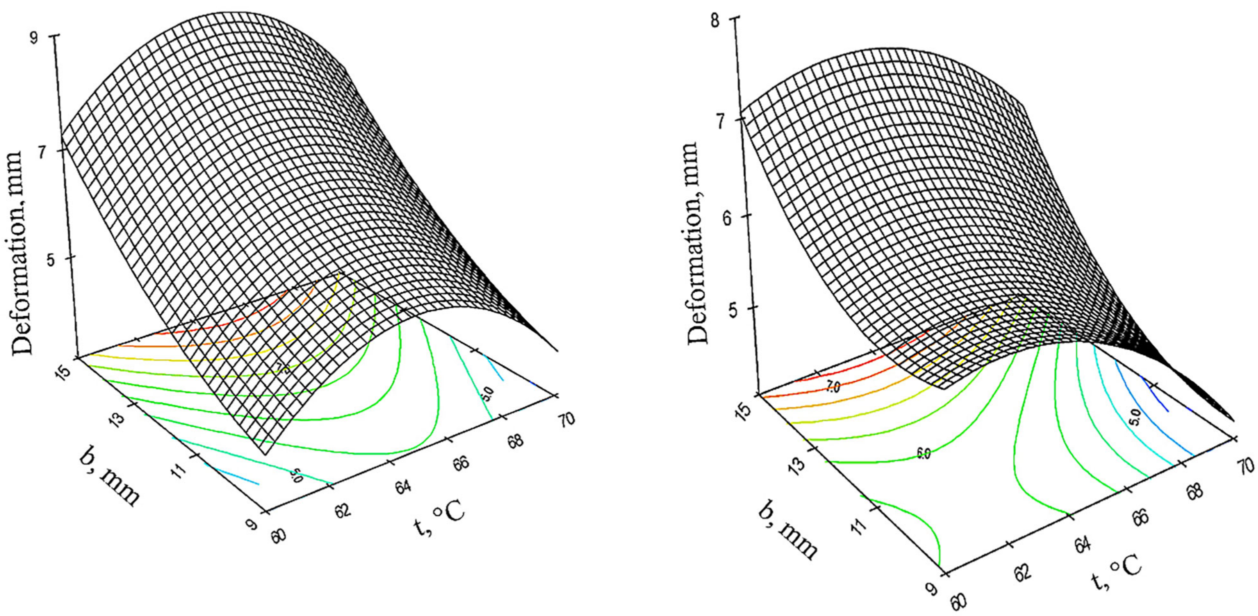


Fig. 5. Influence of drying parameters on the degree of deformation of fruit bars

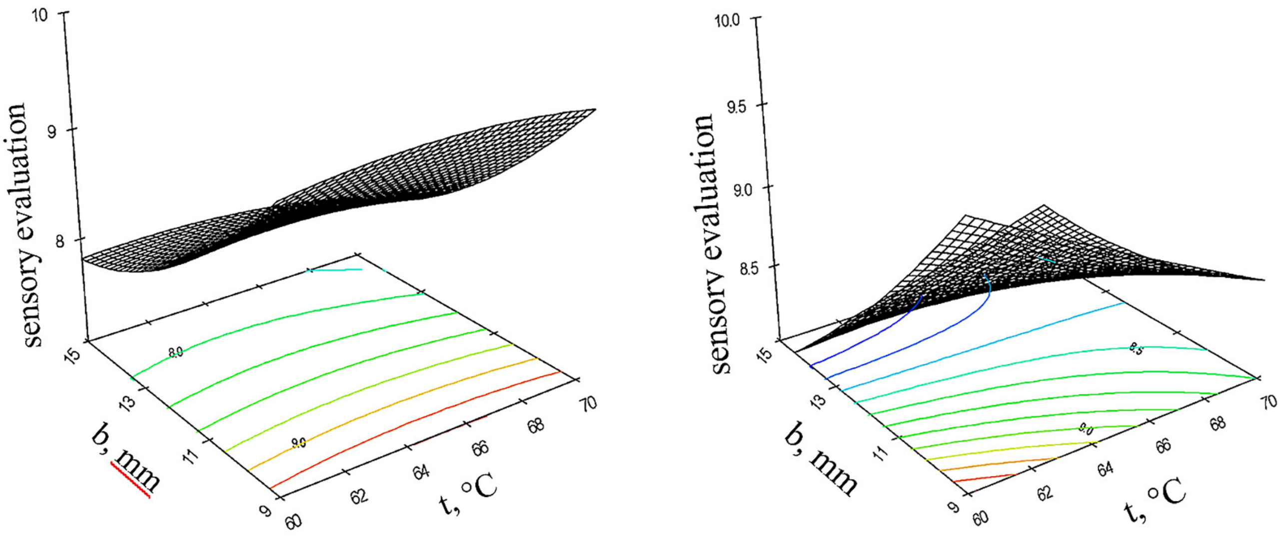
a) for *Chlorella vulgaris* *__b__) for Spirulina Platensis*



In addition to the parameters discussed above, the change in sensory evaluation of the products as the temperature increased was assessed, and the results are presented in Figure 6.

Fig. 6. Influence of drying parameters on the sensory evaluation of fruit bars.

a) for *Chlorella vulgaris* **b)** ***for Spirulina Platensis***



DISCUSSION:

Analysis of Figures 2a and 2b reveals that there is no initial constant-rate drying period. All recorded curves display a falling-rate phase. The shape of the drying curves during this phase depends on the product's composition, structure and size, as well as on the manner in which water is bound within it.

The analysis of the drying-rate curves confirms the observations in Figure 2. A constant-rate drying period is absent, and all curves exhibit a falling-rate period (Figure 3). A second critical point appears in every experimental run. Within the falling-rate region, two sub-periods can be distinguished: (i) a uniform decline and (ii) a non-uniform decline in the moisture-evaporation rate. These sub-periods reflect how the bound water evaporates from the material. The phenomenon can be explained by the complex nature of the product's solid matrix, the relative proportions of the different forms of bound moisture, the mechanisms of moisture transport, and the specific composition of the bars.

The effects of the drying parameters on the drying-rate constants of fruit bars enriched with *Chlorella vulgaris* and *Spirulina platensis* were assessed using non-linear regression models. The drying-rate constants in both formulations are most strongly influenced by the linear effects of drying temperature and fruit-bar thickness.

Fruit bars with Chlorella

$$k*10^3 = 40.6404 - 1.62386*t + 1.78947*b + 0.0151579*t^2 - 0.02*t*b - 0.0245614*b^2, \text{ mim}^{-1} \ (R^2 = 0.88)$$

Fruit bars with Spirulina Platensis

$$k*10^3 = - 37.3544 + 0.624912*t + 2.53713*b - 0.00147368*t^2 - 0.0233333*t*b - 0.048538*b^2, \text{ min}^{-1} \ (R^2 = 0.89)$$

As the temperature rises from 60°C to 70°C, the drying-rate constant (Fig. 4a) increases from 1.1 to 2.7 min^{-1} at a fruit-bar thickness of 9 mm. When the drying temperature and the bar thickness are increased simultaneously, the rate constant grows from 1.1 to 1.6 min^{-1}.

As the temperature increases from 60°C to 70°C, the drying-rate constant rises from 1.1 to 3.5 min^{-1} at a fruit-bar thickness of 9 mm (Fig. 5b). When both the drying temperature and the bar thickness are increased simultaneously, the rate constant grows from 1.1 to 1.9 min^{-1}.

The relationship between the drying parameters and the deformation of the fruit bars was also described by mathematical models.

Fruit bars with *Chlorella*

$$\text{deformation} = - 250.718 + 7.98965*t - 0.959795*b - 0.0618947*t^2 + 0.005*t*b + 0.0502924*b^2 \quad (R^2 = 0.91)$$

Fruit bars with *Spirulina platensis*

$$\text{deformation} = - 78.0526 + 3.04561*t - 2.17383*b - 0.0256842*t^2 + 0.015*t*b + 0.0619883*b^2 \ (R^2 = 0.89)$$

where *t* is drying temperature (°C), *b* is drying-layer thickness (mm).

Drying curves showed the lack of an initial constant rate period, and a clear second critical point, typical of capillary-porous materials. The drying rate coefficients reached 3.5×10^{-3} min^{-1} for the *Spirulina* bars and 2.7×10^{-3} min^{-1} for those with *Chlorella*, with temperature and layer thickness being the most influential factors.

The linear effects of both drying temperature and fruit-bar thickness have the greatest influence on the degree of deformation in both types of fruit bars. As the temperature increases from 60°C to 70°C, the change in deformation is minimal (Figure 5a). When both the drying temperature and bar thickness increase simultaneously, the deformation rises from 5 to 6.7. At a constant drying temperature of

60 °C, increasing the thickness of the fruit bars from 9 to 15 mm leads to a rise in deformation from 5 to 8.5.

As the temperature increases from 60°C to 70°C, the change in deformation for the fruit bars with *Spirulina platensis* is minimal, rising from 4.3 to 5.3 (Figure 5b). When both the drying temperature and fruit-bar thickness increase simultaneously, the deformation increases from 4.3 to 6.7. At a constant temperature of 60°C, increasing the bar thickness from 9 to 15 mm results in a deformation increase from 5 to 7.9.

For the fruit bars with *Chlorella vulgaris*, the change in sensory evaluation is minimal as the temperature increases from 60°C to 70°C, with the highest scores recorded across the tested range (Figure 6a). With a simultaneous increase in drying temperature and fruit-bar thickness, the sensory evaluation of the *Chlorella*-enriched bars decreases from 9.5 to 7.6. At a constant temperature of 60°C, increasing the bar thickness from 9 to 15/ mm leads to a decrease in sensory score from 9.5 to 7.1.

For the fruit bars with *Spirulina platensis*, increasing the temperature from 60°C to 70°C results in a decrease in sensory evaluation from 9.5 to 8.6 (Figure 6b). When both the drying temperature and thickness increase simultaneously, the sensory score drops from 9.5 to 8.0. At a constant drying temperature of 60°C, increasing the bar thickness from 9 to 15mm reduces the sensory score from 9.5 to 7.6.

CONCLUSION:

Depending on the drying-air temperature and tray loading, the drying time for both fruit bar variants with *Chlorella* and *Spirulina platensis* ranged from 7.0 to 18.0 hours.

The absence of an initial constant-rate drying period was observed. All recorded curves exhibited a falling-rate drying phase.

A second critical point was identified in all experimental cases, with two sub-phases noted: a sub-phase of uniform moisture evaporation rate decline and a sub-phase of non-uniform decline.

The most significant effects in both variants were attributed to the linear effects of fruit-bar thickness and drying temperature, the quadratic effect of bar thickness, and the interaction between drying temperature and bar thickness.

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