

## Article

# Evaluating the Performances of Interval Starting Accessibility Drying (ISAD) through Protein and Total Polyphenol Contents of Blue Crabmeat (*Portunus segnis*)

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**Abstract:** Blue crab (*Portunus segnis*) proliferation on Tunisian coasts started in 2014/2015. It has heavily impacted the balance of other species, local biodiversity, and fishing activity. Limiting these drawbacks may be achieved through ways promoting crabmeat. For this purpose, two different drying modes were tested: Conventional convective drying (CCD) and interval starting accessibility drying (ISAD) under 45 °C and relative humidity of 40%. Several air velocities were assayed under CCD: 1.5, 2.5, 3.5, and 5 m.s<sup>-1</sup>. Two different ISAD tests were run with different time-related conditions: drying period of 15 s and tempering period of 15 or 60 s. Drying modes and operating conditions performances were compared through proteins and total polyphenol contents (TPCs) evolution during the treatment. Important polyphenol and protein losses were observed between raw and processed crabmeat. Airflow velocities have a significant effect on crabmeat quality preservation. ISAD method under 15 s/60 s allowed the best preservation of these quality parameters. TPC and proteins losses and kinetics during drying under CCD or ISAD were modelled and correlations were established between the quality parameters, the residual water content at all drying times, and the evaporation rate.

**Keywords:** crabmeat; air velocity; ISAD; continuous drying; proteins; total polyphenols



**Citation:** Gliguem, H.; Hajji, W.; Rekik, C.; Allaf, K.; Bellagha, S. Evaluating the Performances of Interval Starting Accessibility Drying (ISAD) through Protein and Total Polyphenol Contents of Blue Crabmeat (*Portunus segnis*). *Processes* **2021**, *9*, 1698. <https://doi.org/10.3390/pr9101698>

Academic Editor: Dariusz Dziki

Received: 4 August 2021

Accepted: 16 September 2021

Published: 23 September 2021

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## 1. Introduction

For several decades, changes in the Mediterranean Sea have allowed the introduction of invasive marine species. Exotic species invasion is the result of several combined causes such as water warming, maritime traffic, discharge of ballast water, the opening of the Suez Canal, etc. [1,2]. Since 2015, up to 136 invasive species have been recorded on Tunisian coasts, including 34 crustaceans. The majority were Lessepsian species (61.76%) from the Indo-Pacific Ocean [2]. One of these species, *Portunus segnis* (from the Indo-Pacific Ocean), was recorded for the first time in the Gulf of Gabes (Tunisia) in 2014 [3]. These new species of decapods have proliferated on the southern Tunisian coast and gave rise to flowering [4].

Seafood is generally known for its beneficial contribution to human nutrition. Indeed, crabmeat is a good source of essential proteins and minerals, especially calcium, potassium, iron, and phosphorus [5,6]. Crabs are mainly composed of a high protein content, ranging from 14 to 22.6%, as well as of high mineral content [6–8]. Crabmeat has a low lipid percentage of less than 2% [6,9], the majority of which contains polyunsaturated fatty acids (PUFAs), accounting for 32 to 52%, compared to 20 to 28% of the total fatty acid content [8–10]. Premarathna, Rajapakse, Pathirana, Senaratne, Karunarathna and Jayasooriya [5] compared several fish species with a crab species (*P. pelagicus*), and their study showed that PUFAs and monounsaturated fatty acids (MUFAs) were significantly

higher in crabmeat, compared to the content found in fish flesh, while saturated fatty acids (SFAs) were lower in crabmeat.

Due to the large quantities of crabs present currently on the Tunisian coasts, and the high nutritional value of crabmeat, this decapod should be valorised and may be preserved by several techniques in order to set up new food products appreciated by the consumer with a significant nutritional value. Drying may be one of these techniques which will allow the consumer to have ready to use dried crabmeat to incorporate in daily meals such as soups, sauces, etc. However, conventional and innovative drying processes, applied through any mode (convective, infrared, microwave, etc.) often lead to product overheating, resulting in nutrient denaturation, crack formation, and important organoleptic degradation. Indeed, heat treatments negatively affect the nutritional composition and modify the sensory properties of seafood [11]. Proteins, such as many other nutrients, can be modified by drying, in particular seafood proteins, which are sensitive to thermal denaturation [12]. In addition, drying methods and conditions have a significant influence on nutrient degradation [11]. Drying negative drawbacks are essentially related to high-temperature exposure of food material. Indeed, while the surface product temperature of a fresh biological product is lower than the heating air, due to water saturation during the initial drying stage, this temperature rapidly increases with the product water content decrease. Consequently, temperature increases throughout the product during drying. This phenomenon impacts the nutritional and organoleptic properties of dried foodstuffs. On another hand, given the vast literature on the impact of temperature conditions during conventional drying on the quality of final dried products, it is also surprising that so few published drying studies have been reported in the literature about the effect of airflow velocity.

Intermittent drying has been employed with the aim to prevent these drawbacks by minimizing the moisture gradient inside the product during drying. Intermittent drying consists of subjecting the product to repeated active drying periods alternated with rest or tempering periods. During this latter, central water diffusions toward peripheral regions are allowed, resulting in moisture rebalance throughout the drying product and in a reduction of thermal damages. However, intermittent drying processes are based on long active and tempering durations, which eliminate the expected benefits of this method [13–16].

Hence, while using convective drying, an effective method to better preserve nutritional and organoleptic properties would be to maintain the product temperature lower by keeping high surface water content as long as possible during the process. For this purpose, very short heating periods alternating with short tempering ones may be used. In fact, tempering period duration should take into account the time required for water to diffuse toward the product surface while active period duration should be calculated based on surface water evaporation. This process, which has been named interval starting accessibility drying (ISAD) is an intensified new process [17] that aims for a better quality product and an energy-saving drying treatment. Notably, the higher the airflow velocity over the critical airflow velocity (CAV) is, the more beneficial the active periods of the ISAD drying process will be. Indeed, according to Nguyen, et al. [18], CAV is an air velocity from which increasing this parameter has no effect on the drying rate. On the other hand, below CAV, the external transfer “controls” the drying rate, so the airflow velocity variation has an effect on the drying kinetic. Thus, since the product temperature is greatly lower than the airflow temperature, ISAD becomes more adequate for heat-sensitive products than conventional convective drying (CCD). ISAD is then an efficient intensification of the conventional hot air-drying process. Indeed, it actually allows using an airflow velocity significantly higher than the critical CAV value. The tempering periods are devoted to the internal diffusion of moisture within the matrix [17]. The most important key condition to perform a greatly promising ISAD operation is to reach the water homogeneity of water within the material matrix by diffusion during each tempering period.

It is well established that the temperature experienced by a food product during processing is one of the principal agents of food nutrients degradation. CCD imposes on

the product surface, after the constant drying period, increasing temperatures reaching rapidly the dry bulb one, while during ISAD treatments, wet bulb temperatures will be maintained on the surface during longer periods [17].

Phenolic compounds are high nutritional value nutrients, with already proven health benefits. They are also heat-sensitive compounds that may help indicate the extent of the negative impact of the drying method on the product. Similarly, proteins, especially those of seafood origin, are an excellent nutrient for the human diet, owing to several advantages such as high amino acid contents and several functional properties. Unavoidably, proteins would be subject to different thermal stresses during several food processes such as drying. Thus, tracking biochemical and nutritional changes on proteins and total polyphenols contents (TPCs) during drying may be helpful to compare the performances of the drying mode tested and to optimise the operating conditions.

This research aims (i) a comparative analysis between the effects of different airflow velocities during CCD on some quality attributes of crabmeat, (ii) to evaluate and compare the effects of ISAD and CCD processes on proteins and TPC contents of crabmeat, (iii) to validate the optimum drying operating conditions, and (iv) to model the quality attributes behaviour related to the optimum ISAD and CCD drying modes.

## 2. Materials and Methods

### 2.1. Raw Material

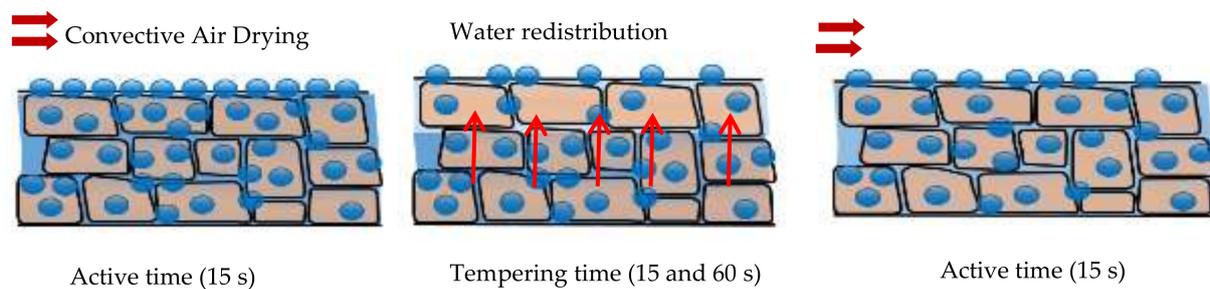
Blue crabs (*P. segnis*) were purchased from a local market of Tunis (Tunisia) and covered immediately with ice while being transported to the laboratory. Before any operation, crabs were sorted by sex and size. To have a lot as homogeneous as possible, the females were removed. The males studied had an average weight of  $216.01 \pm 17.67$  g, with  $6.34 \pm 0.67$  cm and  $12.44 \pm 1.11$  cm of the length and width of the carapace, respectively. After sorting, the crabs were washed, shelled, and breast meat was removed to be dried. Breast meat samples were manually cut with stainless-steel knives, into parallelepipedic slabs of  $2 \times 1 \times 0.2$  cm dimensions. The drying experiments were conducted using slices of crabmeat 2 mm thick.

### 2.2. Drying Experiments

Two different drying methods, i.e., CCD and ISAD, were tested.

CCD was conducted using 2 mm thickness crab samples with approximately  $4.16 \pm 0.72$  g weight, at a constant air temperature of 45 °C and relative humidity of 40%, for a total drying period of 2 h [12] and at different airflow velocities of 1.5, 2.5, 3.5, and 5 m.s<sup>-1</sup> determined through an anemometer (Testo 400; Testo Ag; Lenzkirch, Germany). Previous research studies on seafood convective drying have been conducted at low air velocities from 0.5 to 3 m.s<sup>-1</sup> [19–22]. In this study, a wider range of air velocities was tested in order to understand the kinematic behaviour of crabmeat when drying at higher flow rates and particularly to identify the CAV.

The innovative drying technique, named ISAD, consists of very short periods of active drying/heating ( $t_{ON}$ ) interspersed with tempering times ( $t_{OFF}$ ) of a few dozens of seconds [17] (Figure 1). During the active drying time, the heat source is turned ON and during the tempering period, it is turned OFF. ISAD was conducted on the same crab samples dimensions and was performed with an airflow temperature of 45 °C and low relative humidity of 40%, drying periods ( $t_{ON}$ ) of 15 s, followed by tempering periods ( $t_{OFF}$ ) of 15 and 60 s (Figure 1). The tempering time value was chosen to follow a series of preliminary trials conducted within the research unit (PATIO) and applied to several food matrices such as apple, strawberry, and quince [17].



**Figure 1.** Schematic behavior of water (blue circles) migration and redistribution during ISAD processing.

### 2.3. Compositional Analyses

The determination of crab flesh dry matter was operated in an oven (Memmert SNB100, Schwabach, Germany) at a temperature of  $105 \pm 2$  °C up to a constant weight [23]. The water activity ( $A_w$ ) of raw and dried crab samples was measured using an  $A_w$ -meter (Rotronic Hygrolab 2, Bassersdorf, Switzerland). The pH of raw materials was measured using a portable pH meter (Testo 206-pH2, La Chapelle-sur-Erdre, France) previously calibrated. The probe was directly inserted into the crabmeat, and the pH and temperature values were displayed directly.

Extraction of total lipids from raw and dried materials was applied according to the Folch method [24], based on which 10 mL of chloroform–methanol (2:1) and 1% butylated hydroxytoluene (BHT) mixture were added to 1 g of samples.

Total ash was determined by incineration in a muffle furnace heated at 550 °C for 6 h [25]. Chloride content was analysed as described by AOAC [26]. To determinate the phosphorus, calcium, and magnesium contents, samples were cremated. Then, assays were performed by atomic emission spectrometry with inductively coupled plasma [27].

The protein content was evaluated in fresh and dried crab samples through Kjeldahl [28] and Lowry [29] methods. The Kjeldahl method was only used for raw material and final dried products. The Lowry method was also used as an indicator of protein degradation following the application of the two drying modes, CCD, and ISAD.

For sample preparation, 0.45 g of raw and crabmeat dried under different conditions were crushed in a mortar then homogenised with 9 mL of distilled water until the mixture no longer contains solid debris. This protein solution was used for spectrometric assay through the Lowry method [29]. Protein concentration was determined using bovine serum albumin as standard. The maximum absorbance was obtained at a wavelength of 750 nm [30] using a 6715 UV/V spectrophotometer (JENWAY, Staffordshire, UK).

Total polyphenol content (TPC) was measured in fresh and dried crab samples and was used as another quality indicator to study the impact of drying methods and operating conditions through polyphenol loss during drying. Extraction was performed according to Solari-Godiño, et al. [31], with some modifications. A total of 0.250 g was added to 10 mL of a methanolic solution (50% methanol, 50% distilled water, and 0.1% concentrated HCl). The samples were left in a shaker (in the dark) for 24 h. Then, 500 µL of Folin–Ciocalteu reagent (10%) was added to an aliquot of 100 µL of the methanolic extract. The mixture was left pending for 8 min before the addition of 400 µL of  $\text{Na}_2\text{CO}_3$  (7%). The final volume of the solution is 1 mL. After incubation for 45 min in the dark, the absorbance was measured using a 6715 UV/V spectrophotometer (JENWAY, Staffordshire, UK) at 760 nm. The TPC was expressed in milligrams of gallic acid equivalent per 100 g of dry material (mg GAE /100 g db).

#### 2.4. Polyphenol and Protein Losses Modelling

Nutritional component degradation or losses in food during heat treatments has often been described to follow either a pseudo-zero or a first-order kinetic [32,33]. Component degradation reaction rate equation may be written as follows (Equation (1)):

$$r = \frac{dC}{dt} = -kC^n \quad (1)$$

where  $r$  is the reaction rate,  $C$  is the component concentration at time  $t$ ,  $k$  ( $s^{-1}$ ) is a reaction constant, and  $n$  is the reaction order.

Finding the reaction order requires plotting linear forms of the rate equation (Equation (1)) and calculating the correlation coefficient (Equations (2) or (3)).

$$\text{First - order reaction (n = 1) } \ln(C) = -kt + \ln(C_0) \quad (2)$$

$$\text{Zero - order reaction (n = 0) } C = -kt + C_0 \quad (3)$$

where  $C_0$  is the component concentration at time  $t_0$  (the raw material before drying).

Mean square error (MSE), reaction constant ( $k$ ), and coefficient of determination ( $R^2$ ) were used as a statistical criterion to evaluate the prediction efficiency.

#### 2.5. Statistical Analysis

Drying tests at each inlet air velocity and all analyses were performed at least in triplicate ( $n = 3$ ) except for the determination of phosphorus, calcium, and magnesium ( $n = 2$ ). The results were expressed as mean  $\pm$  standard deviation. Statistical analyses of experimental data were performed with the Statgraphics Centurion software (XVII 17.01.0012, 2016, The Plains, VA, USA), with the source of variance being the airflow velocity, and tempering time. To test the significance of these operating conditions, effects on TPC and protein content, ANOVA tests were performed and carried out using multiple range tests at a significance level of  $p$ -value  $< 0.05$ .

### 3. Results

#### 3.1. Physicochemical Composition of Raw Material

As blue crabs' presence on Tunisian coasts is recent, it seems important to place their composition in a more general context by comparing it to the values found in the literature. Table 1 summarises the composition of the crabmeat studied in this work. The breast muscle tissues of the blue crab used in this study have an initial water content of  $79.9 \pm 1.19\%$  on a wet basis (wb), a lower value than that found by Béjaoui, Ghribi, Hatira, Chetoui, Rebah and Cafsi [10] for the same species in Tunisia (85–88%). This variation could be due to the collection site [34,35] and the seasonal variation in the composition of the flesh [9]. However, the average water content was close to the value found by Wu, Zhou, Cheng, Zeng, Wang and Feng [8], 79.5%, for the same species. Other blue crab species have similar water contents of 80.12 and 79.05% for *Callinectes Sapidus* recorded, respectively by Zotti, Del Coco, De Pascali, Migoni, Vizzini, Mancinelli and Fanizzi [6] and Küçükgülmez, et al. [36].

**Table 1.** Proximate composition of raw crabmeat (*Portunus segnis*).

Physicochemical Parameters (g/100 g of Raw Sample)	Value
Water content	79.9 ± 1.19
Aw	0.88 ± 0.007
pH	6.62 ± 0.13
Ash	2.10 ± 0.24
Lipids	1.86 ± 0.04
Chlorides	1.40 ± 0.09
Proteins (Kjeldahl)	14.89 ± 0.29
Proteins (Lowry)	15.34 ± 0.37
TPC (mg GAE/100 g wb)	96.1 ± 1.65
Minerals (mg/100 g of raw sample)	
Ca	72.6
Mg	42.0
P	231.0

Aw and pH values were acceptable for fresh crab. Compared to *Callinectes Sapidus* meat whose pH was 6.48 [37], the pH of *Portunus Segnis* in this study (6.62) was slightly higher.

Crabmeat contains a high fraction of ash ( $2.1 \pm 0.24\%$ ). This observation was made by most researchers on different crab species with values varying between 1.63 and 2.55% [6–8,38,39]. Crabmeat lipid content was analyzed to be less than 2% as confirmed by Benjakul and Sutthipan [40], Moronkola, et al. [41], and Zotti, Del Coco, De Pascali, Migoni, Vizzini, Mancinelli and Fanizzi [6]. Such a composition makes the crabmeat particularly interesting nutritionally. Meanwhile, chloride content in crabmeat was found to be  $1.4\% \pm 0.09$ , slightly higher than that recorded by Benjakul and Sutthipan [40].

The protein content was evaluated in fresh crab samples through Kjeldahl and Lowry methods (Table 1). Proteins are the largest fraction after water in crabmeat according to the Kjeldahl standard method ( $14.89 \pm 0.29\%$ ) and also to the Lowry method ( $15.34 \pm 0.37$ ). The Kjeldahl method was used in this study to allow comparison with other published results in the literature. Indeed, the protein content measured according to the Kjeldahl method (Table 1) is lower than the one found by Wu, Zhou, Cheng, Zeng, Wang and Feng [8] which was 16.9% for male invidious. Similarly, Gokoglu and Yerlikaya [7] and Ayas [42] obtained for the same species, significantly higher levels of 22.64% and 20.75–21.17%, respectively. However, other crab species have a protein content close to that found in this study, 14.31% for *Scylla serrata* [40] and for blue crab *Callinectes Sapidus*, 15.13% [6], and also 14.71% according to [7]. These variations may be due, according to Musaiger and Al-Rumaidh [43], to the influence of several intrinsic and extrinsic factors such as age, sex, season, etc.

Miki [44] described the presence of carotenoids in marine fish and shellfish and highlighted their scavenging effect against active oxygen. Some sea products, such as shrimp, contain high levels of TPC, i.e., carotenoids with high antioxidant properties. Crabs have an omnivorous diet with substantial amounts of algae, both brown and green [45], leading to the presence of polyphenols in their flesh. From an extensive literature review, there have been no recorded data about the determination of polyphenols in fresh crabmeat. The TPC was  $96.1 \pm 1.65$  mg GAE/100 g of fresh material (Table 1). This value was lower than that found by Solari-Godiño, Pérez-Jiménez, Saura-Calixto, Borderías and Moreno [31] for anchovies (200 mg GAE/100 g of fresh material).

Calcium, phosphorus, and magnesium are among the minerals present in abundance in blue crabmeat. Calcium and magnesium were present in crab fresh tissue at 72.6 and 42 mg/100 g wb, respectively (Table 1). These values were very close to those found

in *Portunus Pelagicus* (87.6 and 48.8 mg/100 g wb, respectively) and *Callinectes Sapidus* (64.9 and 37.1 mg/100 g wb, respectively) according to Gokoglu and Yerlikaya [7]. However, the phosphorus content, which was 231 mg/100 g wb (Table 1), was very close to the value found by Küçükgülmez, Celik, Yanar, Ersoy and Çikrikçi [36] for the blue crab *Callinectes Sapidus* (202.16 mg/100 g wb)], but it was higher than phosphorus contents of *Portunus Pelagicus* (154.2 mg/100 g wb) and *Callinectes Sapidus* (120.6 mg/100 g wb) [7].

### 3.2. Effect of Continuous Drying Airflow Velocity on Polyphenol and Protein Contents

#### 3.2.1. Effect of CCD Airflow Velocity on TPC

Table 2 shows results obtained for TPC after drying at different airflow rates. CCD application negatively affected the quality of dried crabmeat and brought degradation of bio-functional food compounds. Indeed, important polyphenol losses were observed between raw and processed crabmeat.

**Table 2.** Effect of air velocity on polyphenol and protein contents of dried crabmeat.

	Fresh Crab Meat Samples	Airflow Velocity (m.s <sup>-1</sup> )			
		1.5	2.5	3.5	5
TPC (mg GAE/100 g db)	472.39 <sup>a</sup> ± 3.57	212.26 <sup>b</sup> ± 7.71	188.81 <sup>c</sup> ± 7.12	186.91 <sup>c</sup> ± 0.7	201.59 <sup>b,c</sup> ± 1.85
Protein content (g/100 g db) Lowry	76.87 <sup>a</sup> ± 2.92	33.09 <sup>b</sup> ± 1.23	32.93 <sup>b</sup> ± 1.09	31.53 <sup>c</sup> ± 0.84	28.77 <sup>c</sup> ± 1.31

Data are recorded as the mean ± standard deviation. Values having the same lowercase letter (a, b, and c) for TPC and protein contents are not significantly different at a confidence level of 95%.

It is worth noting that research studies dealing with animal sources of antioxidants are very limited and even rarer when it comes to polyphenol antioxidant activity in these products. Investigations on TPC and effects of processing on their contents have mainly concerned fruits and vegetables. Hence, very few results have been found describing the evolution of TPC in meat or fish products during thermal processing [31].

Most generally, thermal treatment will lead to total polyphenols oxidation, thermal degradation, and reduction of their antioxidant activity. Specifically, in animal-derived products, this latter property is related to the presence of proteins, peptides, and amino acids as well as to vitamin E [46]. Polyphenols losses due to heat treatment [47] may lead to chemical structure modification and to the binding of polyphenols to other compounds of the matrix such as proteins [48]. In fact, it is the combined effect of temperature and exposure time that affects polyphenol contents. High protein content in meat or seafood products may influence the behaviour of TPC degradation reaction since these molecules react with proteins.

Alean, et al. [49], in their work on the effects of drying on cocoa polyphenols contents, observed that these compounds depend on the product moisture during drying and explained their behaviour by the total polyphenol's volatility and by the synergy between water and total polyphenols due to polarity. Hence, water presence permits dissolving polyphenols to lead them to the product surface. This finding allows explaining the higher concentration of TPC observed for lower airflow velocity 1.5 m.s<sup>-1</sup> (212.62 mg GEA/100 g db) compared to other ones (Table 2). Indeed, the lowest TPC recorded were those of samples, with 188.81 and 186.91 mg GAE/100 g db under 2.5 and 3.5 m.s<sup>-1</sup>, respectively. The slightly higher TPC found under 5 m.s<sup>-1</sup> (201.59 mg GEA/100 g db) may be explained by the crust formation at the surface of the product when air velocities were high, which may hinder water movement. Indeed, according to air velocity impact on the rate of water elimination, water that migrates to the surface carries solutes from the food, originating tensions in the structure, which may cause some changes in mechanical properties and profound physical and chemical alterations on the surface, thus leading

to the formation of a hard impenetrable surface layer, which keeps the foods dried at the surface but moist inside [50,51].

### 3.2.2. Effect of CCD Airflow Velocity on Protein Content

Protein losses during drying were evaluated according to the Lowry method. In fact, the Lowry assay is a fast spectroscopic method, less expensive, and easy to implement if compared with the Kjeldahl method, hence more adequate to use while monitoring protein amounts or losses during drying kinetics. Protein content decreased with airflow velocity increasing (Table 2). Indeed, heat treatments can lead to many changes in food protein contents, such as the destruction of sulphur amino acids, as in the case of milk proteins [52], meat [53], fish flesh, and seafood [54].

According to Table 2, Lowry assay showed a drastic decrease in protein content after drying, from  $76.87 \pm 2.92$  g/100 g db down to  $28.77 \pm 1.31$  g/100 g db for samples dried at  $5 \text{ m.s}^{-1}$ . No significant change in protein content was observed for airflow rates up to  $2.5 \text{ m.s}^{-1}$ . However, further significant degradation was noticed under 3.5 and  $5 \text{ m.s}^{-1}$  drying air velocities. At these higher rates, the hot air drying flowing over the surface causes more water evaporation in the product. Hence, the product surface reaches the dry-bulb temperature faster since water, when available, is more rapidly removed from the surface at higher flow rates. Thus, proteins undergo the constant air-drying temperature ( $45^\circ\text{C}$ ) during a longer exposure leading to higher losses [55] which were indicated by the lower protein content ( $28.77 \pm 1.31$  g/100 g db) measured under  $5 \text{ m.s}^{-1}$  drying airflow rate. This may be correlated with drying kinetics where no flow rate effect was observed up to  $3.5 \text{ m.s}^{-1}$  and support findings previously cited on CAV by Nguyen, et al. [22] and Hajji, Bellagha and Allaf [17], i.e., once the air velocity is above a certain threshold, CAV, the continuous drying kinetics is revealed by the phenomenon of efficient diffusion of humidity inside food matrix. Indeed, when the drying process is characterised by negligible external resistance (NER), the kinetics of the internal diffusion transfer of water is, in this range of airflow, the process limiting during hot air drying.

Interestingly, the effect of airflow velocity on dried food quality has been well highlighted in this research. In fact, increasing airflow velocity induced carrying a larger volume of air over the surface of the crabmeat sample and evaporating more water when available on the product surface. This leads to several changes in protein and polyphenol contents in crabmeat samples.

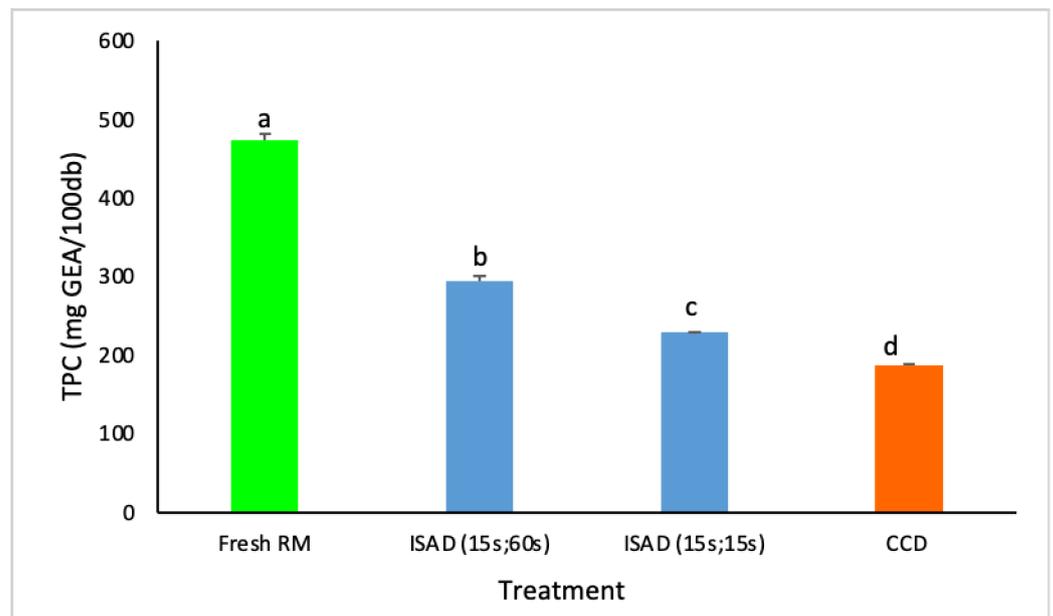
### 3.3. Effect of Drying Mode (CCD versus ISAD) on Polyphenol and Protein Contents

For crabmeat samples dried at air relative humidity of 40% and at a temperature of  $45^\circ\text{C}$ , the estimated critical airflow velocity (CAV), under which crabmeat drying becomes a diffusion-controlled process exceeds  $2.5 \text{ m.s}^{-1}$ . For these reasons, CCD and ISAD were run under an air speed of  $3.5 \text{ m.s}^{-1}$ .

ISAD treatments with active drying periods of 15 s and tempering periods between 15 and 60 s were tested under the same operating conditions as for CCD. In order to check the efficiency of either method, the impacts on total polyphenol and protein contents were analysed.

#### 3.3.1. Effect of Drying Mode (CCD versus ISAD) on Polyphenol Content

Figure 2 shows the effects of drying modes on TPC. Even though both CCD and ISAD methods, under the conditions tested, have led to an important decrease in TPC, interestingly, the application of the ISAD technique under 15 s/60 s limited the deterioration of these components.



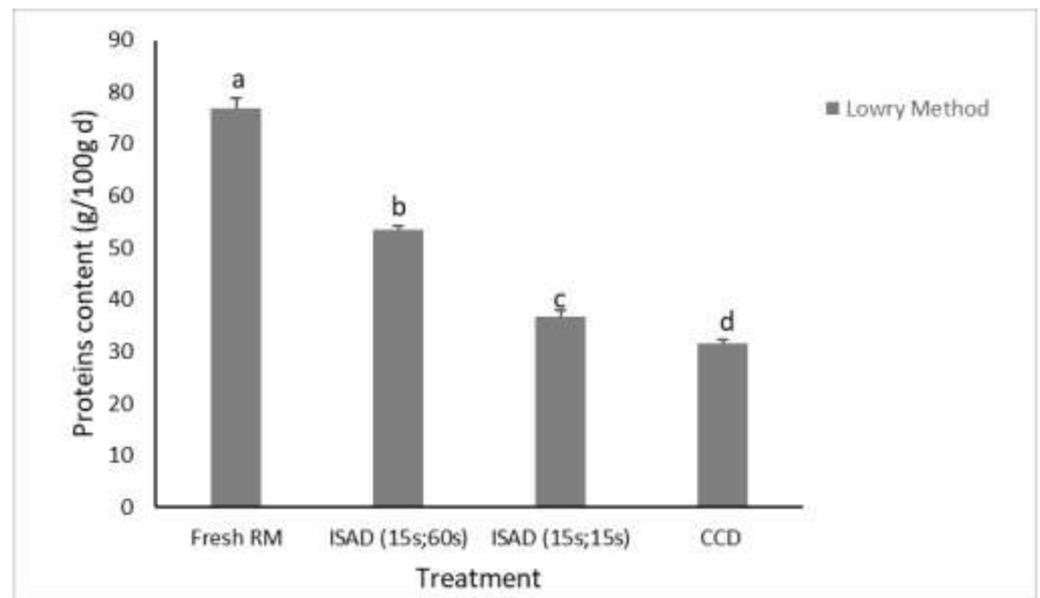
**Figure 2.** Effect of drying method on the TPC of crabmeat. Values having the same lowercase letter (a, b, c, and d), for the TPC of fresh raw material (fresh RM) and dried crabmeat are not significantly different at a confidence level of 95%.

Owing to the tempering period, diffusion allows rewetting the exchange surface. The great evaporating rate prevents overheating and thereby decomposition of polyphenol compounds of crabmeat. Furthermore, the ISAD technique with a 60 s tempering time resulted in a lower evaporating wet-bulb temperature and a better TPC retention. Indeed, the higher the amount of water that reaches the surface during tempering time, the greater the part of heat devoted to the evaporation is. This allows the surface and wet-bulb temperature to stay low, and crabmeat was better protected against overheating. During tempering periods, the additional moisture will also limit the risk of over-drying at the surface, which can lead to excessive dehydration stresses often accompanied by crust formation. In addition, the reduced exposure to elevated temperatures also induced better product quality, as active compounds were better retained [56].

Hence, this result may be explained by the larger value of  $t_{OFF}$  (60 s) which led to a lower temperature experienced by the sample. Indeed, hot-air drying has been described as the drying process with the strongest degradation effect on TPC [57]. These last authors also stated that total polyphenol (flavonoid) thermal sensitivity is related to their structure and to the presence of water in their environment.

### 3.3.2. Effect of Drying Mode (CCD *versus* ISAD) on Protein Content

Figure 3 shows the results of the comparative effects of CCD and ISAD on protein contents. Lower protein content losses were observed when crabmeat slices were ISAD dried with an active period of 15 s and a tempering period of 60 s. Hence, longer rest periods allow water to equilibrate throughout the product maintaining its temperature lower, protecting proteins from heat degradation [17]. Moreover, the Lowry assay clearly highlighted the effect of ISAD rest time through the higher protein losses recorded when the ISAD tempering time decreased from 60 s to 15 s.



**Figure 3.** Effect of drying method on the protein content of crabmeat. Values having the same lower-case letter (a, b, c, and d) of fresh raw material (fresh RM) and dried crabmeat are not significantly different at a confidence level of 95%.

Even though ISAD treated samples showed higher protein levels than those reached under the CCD process, observed losses were higher when tempering time was shorter. Indeed, the expected role of this period is the diffusion of water towards the surface. A higher protein loss would mean that water dragged to the surface during a short  $t_{OFF}$  was not able to adequately rewet the surface and lessen the heating energy and temperature. This may be due to a too short tempering time or to low residual water in the product. Changes in structure and in muscle texture of bighead carp muscle were previously observed, due to collagen denaturation [58,59]. Indeed, Qixing, Zhengran, Shuoshuo, Yanshun, Fengyu, Xueqin, Peipei and Wenshui [59], in their work on temperature effect on the protein composition of bighead carp muscle, observed that longer heating periods affect protein solubility through protein denaturation and production of low molecular weight molecules.

The protein content according to the Lowry method was more important for ISAD treatment than for the CCD mode and for ISAD rest time of 60 s than for 15 s. These observations may be consistent with the hypothesis of the oxidative degradation of amino acids during drying since the Lowry method is closely dependent on the composition of certain amino acids (tryptophan and tyrosine in particular).

### 3.4. Performances of Optimum ISAD Treatment

Quality parameters indicated that the optimal drying treatment among the ones tested in this work is the ISAD method under 15 s/60 s. Indeed, polyphenol and protein contents were higher in the final product treated under ISAD (15 s/60 s) than in the CCD samples or the ISAD (15 s/15 s) ones. Thus, the rest of this work was conducted with the optimum ISAD parameters in comparison with the CCD process under equal drying air operating conditions.

#### 3.4.1. Effects on Physicochemical Losses

The optimum ISAD specific treatment (15 s/60 s) was compared to CCD based on several physicochemical parameters (Table 3).

**Table 3.** Comparison between losses in physicochemical components of dried crabmeat by the optimum ISAD parameters and the CCD under the same conditions (45 °C, 40% relative humidity, airflow velocity: 3.5 m.s<sup>-1</sup>, total drying time: 2 h).

Parameters (% loss)	ISAD (15 s/60 s) Effective Drying Time = 15 min	CCD Effective Drying Time = 120 min
Proteins		
Kjeldahl	14.50 <sup>a</sup>	12.28 <sup>a</sup>
Lowry	34.57 <sup>a</sup>	60.50 <sup>b</sup>
Polyphenols	43.45 <sup>a</sup>	67.41 <sup>b</sup>
Lipids	12.95 <sup>a</sup>	14.54 <sup>a</sup>
Ash	11.97 <sup>a</sup>	18.09 <sup>a</sup>
H <sub>2</sub> O	74.30 <sup>a</sup>	79.68 <sup>b</sup>
Aw decrease	35.43 <sup>a</sup>	37.04 <sup>b</sup>

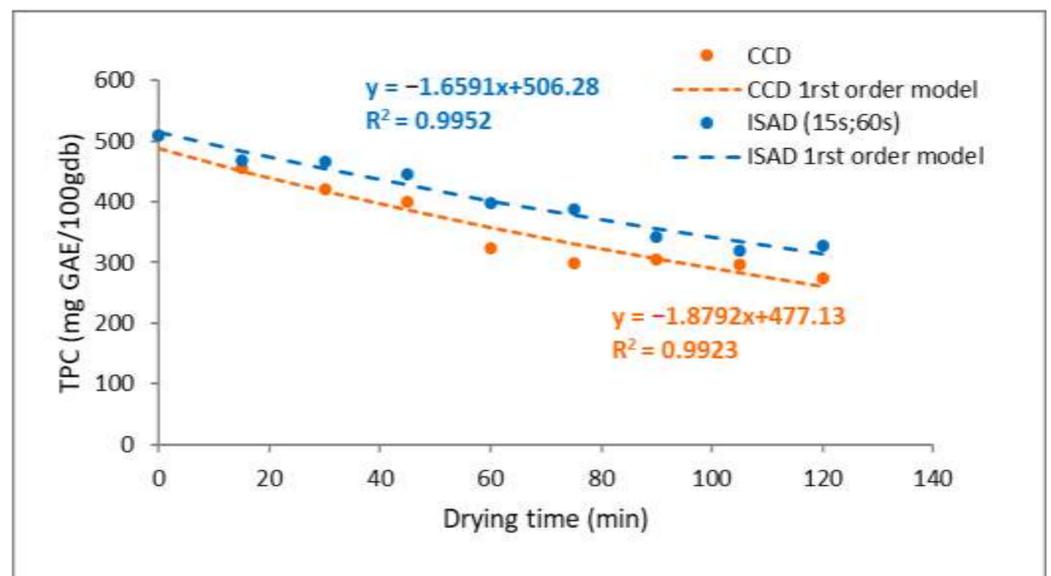
Data are recorded as the mean  $\pm$  standard deviation. Values having the same lowercase letter (<sup>a</sup>, and <sup>b</sup>) for different physicochemical parameters are not significantly different at a confidence level of 95%.

Concerning proteins, which are the second most abundant component after water in crabmeat, no significant difference between the two drying modes in terms of total nitrogen was observed (Kjeldahl method). However, the results of the Lowry method showed that ISAD mode preserved proteins much better than CCD. Results of Table 3 confirmed that the Lowry method is more adequate than the Kjeldahl one to better highlight the link between thermal losses of protein and drying processing parameters. Furthermore, a significant increase in the protein losses was recorded between the fresh crabmeat and the dried one, regardless of the drying method. Such a result was also observed during shrimp drying, in which the protein content decreased from 86.21% db to 85.64 and 84.89% db for convective and solar drying, respectively [60]. The increase in protein losses during drying may be related to the degradation of these proteins and the incidence of browning reactions, by which a certain amount of amino acids is consumed [60,61]. Similarly, ISAD mode preserved polyphenols much better than CCD owing to the lower product temperature maintained throughout the drying process.

For lipids and ash, there was no significant difference in losses between the two drying modes. This was not the case for the water component since the water loss and the decrease in water activity were greater for the CCD mode. In fact, this is intimately correlated to the evolution of water content during the effective drying time of both CCD and ISAD processes. As previously mentioned by Hajji, Bellagha and Allaf [17], the effective drying time represents the total time in which the product remains in the dryer with the heating switched ON. Interestingly, within the used tempering time of 60 s, the effective time required to reach an amount of  $20.47 \pm 0.56$  g H<sub>2</sub>O/g wb is only 15 min, compared to 120 min to reach a final water content of  $16.18 \pm 1.33$ . Hence, ISAD treatment allows reaching lower moisture content and Aw during a shorter effective drying time when compared with the CCD.

### 3.4.2. Polyphenols Degradation Kinetics

TPC has been evaluated during CCD and ISAD processes throughout the drying period (Figure 4). Indeed, the kinetics of TPC evolution related to drying mode may highlight different behaviours throughout the process.



**Figure 4.** Experimental and predicted TPC evolution of crabmeat during CCD and ISAD (15 s/60 s) under the same airflow velocity:  $3.5 \text{ m}\cdot\text{s}^{-1}$ .

Total polyphenols degradation during drying of plant products has often been studied as a function of the drying temperatures [62]. Investigating the effect of the drying mode on the TPC of animal products during the process is rarer. Figure 4 shows a clear decrease in TPC during CCD and ISAD. However, ISAD treatment allowed keeping a higher TPC throughout the process ( $p < 0.05$ ). This may be directly related to the lower temperature undergone by the product under ISAD conditions.

A reaction rate equation (Equation (1)) may be applied to model polyphenol degradation during drying (Equations (2) and (3)) [32,33]. When applying these equations to the TPC obtained during drying of crabmeat by ISAD and CCD (Figure 4), a first-order ( $n = 1$ ) reaction was found to better fit the experimental degradation kinetics. Hence, an exponential decrease in TPC was observed, either eliminated or transformed into other components per unit drying time. It becomes also clear that the rate of the total polyphenol elimination was proportional to the initial TPC concentration in the crabmeat sample.

Hence, exponential type equations (Equations (4) and (5)) may be used ( $R^2 > 0.93$ ) to predict total polyphenols evolution during drying by the following two tested modes:

$$\text{CCD mode : } P_t = P_0 e^{-0.0052t} \quad (4)$$

where  $P_0 = 487.84 \text{ mg GAE}/100 \text{ g}$

$$\text{ISAD mode : } P_t = P_0 e^{-0.0041t} \quad (5)$$

where  $P_0 = 513.67 \text{ mg GAE}/100 \text{ g}$ .

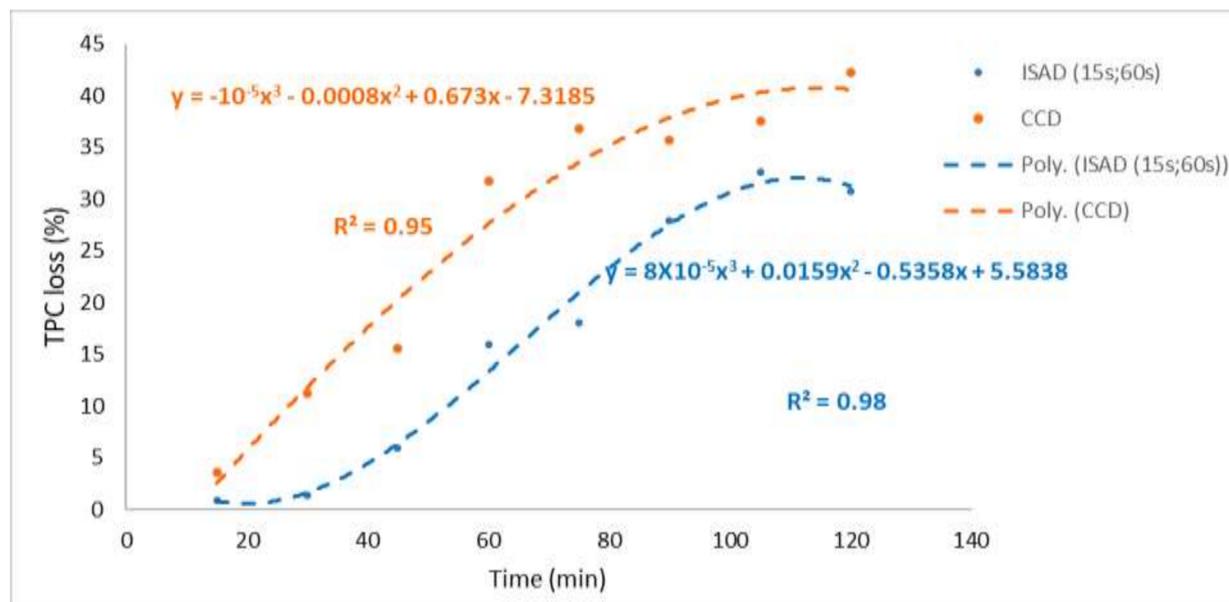
Where  $P_0$  and  $P$  are the predicted TPC in the raw material and at time  $t$ , respectively.

The total polyphenols rate constant obtained by CCD was higher than ISAD's one (Table 4) corroborating the expected results of a lesser impact on the temperature-sensitive component of the latter mode. Once again, the ISAD process, while allowing maintaining lower product temperature throughout the drying process, slowed down the rate of the total polyphenol degradation.

**Table 4.** Kinetics parameters (first order) of TPC evolution of crabmeat during CCD and ISAD under the same conditions.

Drying Mode	k (mg GAE/100 g.min)	$P_0$ (mg GAE/100 g)	$R^2$	MSE
CCD	0.0052	487.84	0.9327	0.0029
ISAD (15 s/60 s)	0.0041	513.67	0.9586	0.075

Total polyphenols losses during drying under the two tested modes are presented in Figure 5. Total polyphenols degradation occurs mostly through oxidative reactions, which are temperature sensitive. Hence, polyphenol losses are expected under drying conditions such as relatively high-temperature/long-time which leads to cellular destruction. At the same time, it is also important to notice that water content in the product allows total polyphenols to dissolve and be led towards its surface, thus either, to suffer oxidation or elimination due to total polyphenol degradation [49]. Hence, it can be observed that, as the drying process progresses, and water content decreases in the product, the rate of total polyphenol loss slows down (Figure 5).



**Figure 5.** Effect of the drying method on degradation kinetics of polyphenols of crabmeat at ISAD (15 s/60 s) and CCD under the same airflow velocity:  $3.5 \text{ m}\cdot\text{s}^{-1}$ .

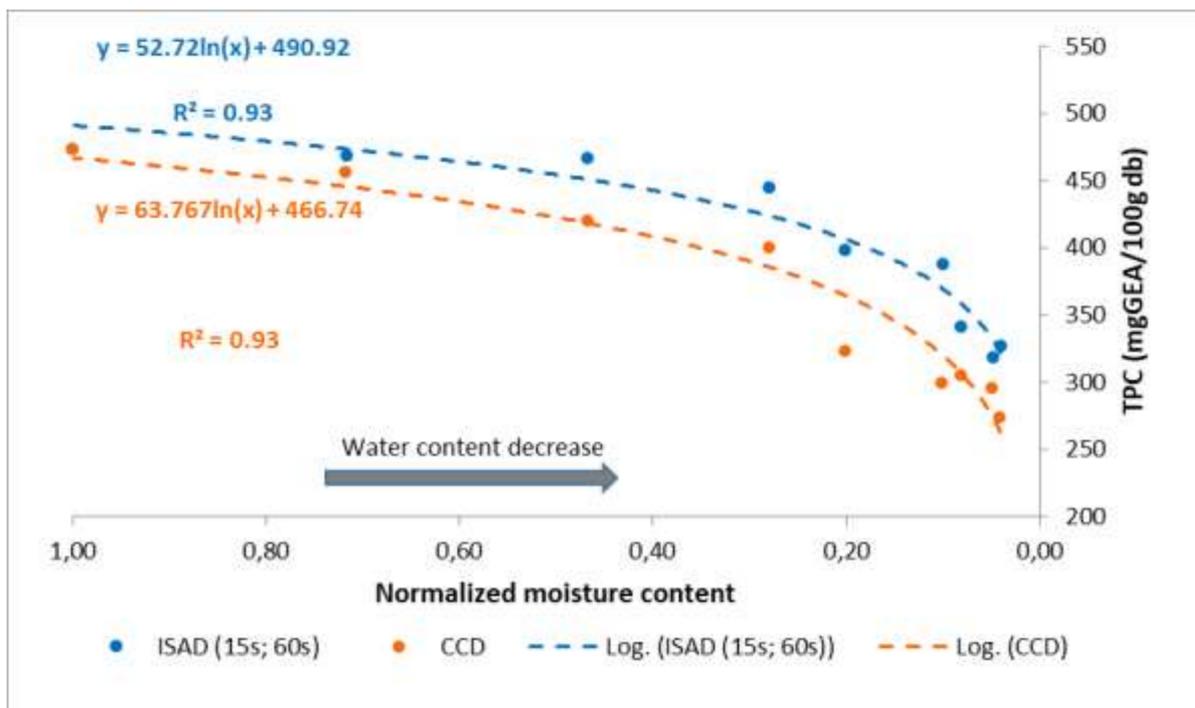
As polyphenols degradation is an oxidation reaction, its rate may be correlated to water content kinetics during drying. Figure 6 shows a logarithmic correlation between moisture content during drying by CCD or ISAD modes, as described by Equations (6) and (7), respectively.

$$\text{CCD mode : TP} = 63.767 \ln(X_N) + 466.74 \quad R^2 = 0.935 \quad (6)$$

$$\text{ISAD mode : TP} = 52.72 \ln(X_N) + 490.92 \quad R^2 = 0.939 \quad (7)$$

where TP is TPC at time t of the drying process, and  $X_N$  the normalised water content, i.e., water content at time t over initial water content expressed on the dry basis (db).

Equations (6) and (7) highlight the close relationship between water evaporation and TPC decrease during drying. Hence, as water moves towards the surface during drying, total polyphenols molecules are dissolved and carried with it [33,49]. Meanwhile, as drying continues, the water content decreases, the product surface temperature rises, further reinforcing the drawbacks on product quality among which are total polyphenols losses.



**Figure 6.** Correlation between moisture content and TPC of crabmeat during CCD and ISAD under the same airflow velocity:  $3.5 \text{ m.s}^{-1}$ .

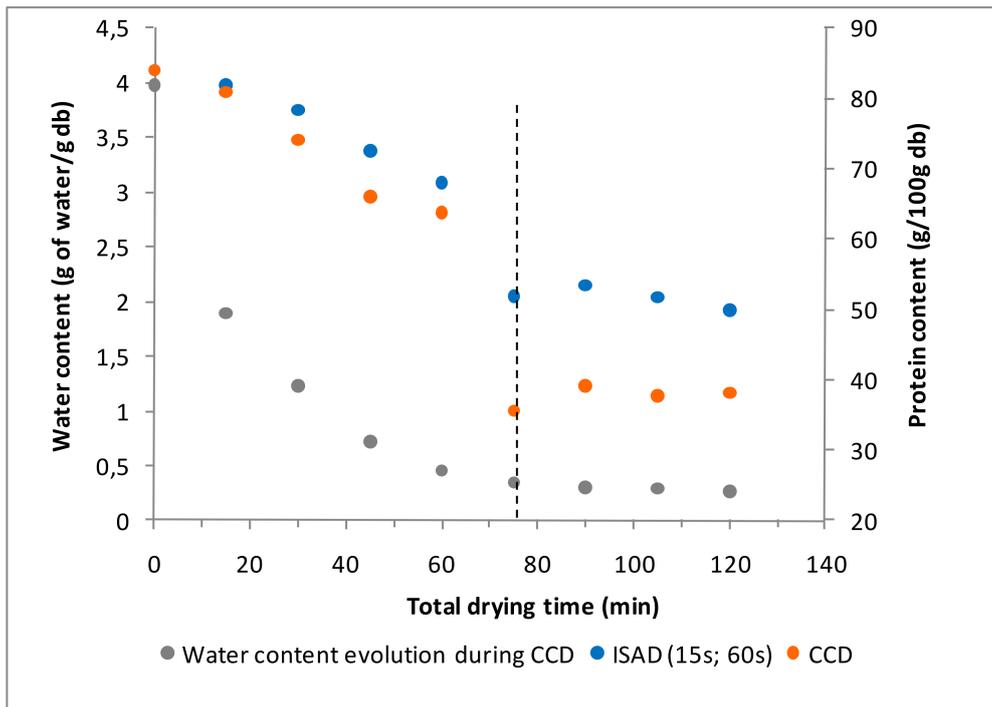
### 3.4.3. Protein Degradation Kinetics

Monitoring protein degradation kinetics during drying is important to highlight the impact of the process mode and parameters on the amount of protein content. Numerous researchers have investigated the effect of thermal stresses (drying, cooking, heating, etc.) on the surface composition, structure, and functionalities of proteins. However, there are limited studies on drying kinetics [63].

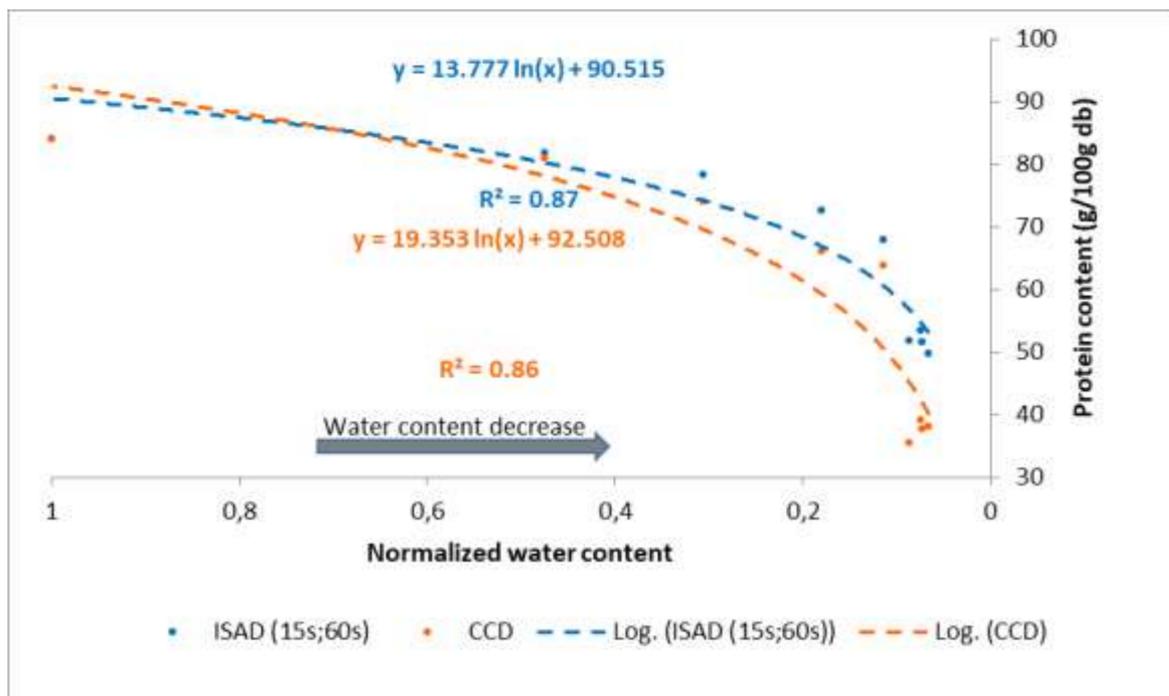
The impact of the drying mode (ISAD *versus* CCD) and conditions (time, airflow velocity, and temperature) on protein and water contents of the blue crabmeat is elucidated in Figure 7.

The decrease in the amount of protein, either with ISAD or CCD was quasi similarly sensitive to the drying time between 0 and 60 min, with slightly higher protein content with ISAD, compared to CCD. During this period, the water content of the crabmeat sample decreased considerably, reaching a loss of 88.58%. From 75 min, a sharp decrease in the protein content was observed for the crabmeat samples dried by CCD, after which the protein amount remained stable in both samples; the ISAD drying preserved significantly higher protein content.

This trend was closely linked with the water loss kinetic (Figure 7). As the presence of water favors heat degradation of proteins and loss of their biological activity [64], as soon as the water content reached a low critical value, maintained stable at the order of 0.3 g of water/g db, the protein content ceased to decrease and remained stable, meaning that their degradation was fading. This is also confirmed through the correlation between these two parameters, as shown in Figure 8, in which the determination coefficients of the logarithmic plot of protein content kinetics in dried crabmeat samples under CCD and ISAD treatment were 0.8618 and 0.8788, respectively.



**Figure 7.** Evolution of water and protein contents of crabmeat during CCD and ISAD (15 s/60 s) under the same airflow velocity:  $3.5 \text{ m.s}^{-1}$ .



**Figure 8.** Correlation between water and protein contents of crabmeat during CCD and ISAD under the same airflow velocity:  $3.5 \text{ m.s}^{-1}$ .

Since the protein assay was performed by the Lowry method which is based on the reactive characteristics of amino acids [29], and as the oxidative degradation of amino acids requires the presence of water, the results of Figures 7 and 8 well confirmed the correlation between the water content and the protein content kinetics during drying.

#### 4. Conclusions

A new drying method, i.e., ISAD, was tested on crabmeat dehydration. This method, which considers very short active drying times ( $t_{ON}$ ) interspersed by very short tempering periods ( $t_{OFF}$ ), was compared to CCD. Optimums were considered based on the best retention of protein content and TPC.

As a first step, effects of drying air velocity during CCD were tested, which allowed identifying a critical air velocity of  $3.5 \text{ m}\cdot\text{s}^{-1}$ . In addition, an air velocity of  $3.5 \text{ m}\cdot\text{s}^{-1}$  allowed better conservation of the quality parameters. In the second step, using this confirmed operation condition, ISAD was applied through two different time-related conditions ( $t_{ON}$ ,  $t_{OFF}$ ): (15 s, 15 s) and (15 s, 60 s). Comparison between results obtained under CCD and the two ISAD conditions revealed a better protein and TPC retention under ISAD (15 s, 60 s). TPC and protein content values highlighted the specific effect of the temperature undergone by the product during drying, which requires the presence of water. This phenomenon was confirmed by the high correlation observed between either the TPC or the protein content, and the residual water content during drying through different modes. ISAD treatment, while allowing rewetting the crabmeat slice during the tempering periods, maintained the product temperature close to the wet-bulb temperature. This lower temperature limits the side effects of dried food quality. ISAD treatment appeared as an effective drying method which may be easily implemented in various drying units. It is, however, necessary to underline the importance of the identification of the time-related ISAD conditions.

**Author Contributions:** Conceptualisation, methodology, investigation, formal analysis, data curation, writing—original draft preparation, writing—review and editing, H.G.; conceptualisation, methodology, investigation, formal analysis, data curation, writing—original draft preparation, writing—review and editing, W.H.; methodology, investigation, formal analysis, data curation, C.R.; visualisation, validation, K.A.; conceptualisation, methodology, investigation, validation, writing—original draft preparation, writing—review and editing, S.B. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

**Conflicts of Interest:** The authors declare no conflict of interest.

#### Abbreviations

ISAD	Interval starting accessibility drying
CCD	Conventional convective drying
TPC	Total polyphenols content
CAV	Critical air velocity
db	Dry basis
wb	Wet basis

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