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A Novel Optimization Algorithm for *Echium amoenum* Petals Drying

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Abstract: A novel multi-objective optimization algorithm was developed, which was successfully applied in the drying process. The effect of drying parameters (air velocity (v_d), drying temperature (T_d)) on the energy consumption (EC) and the quality parameters of *Echium amoenum* petals in fluidized drying were experimentally studied. The following quality parameters were examined: the color difference, the bioactive compounds as losses of total antioxidant capacity (TAC) and losses of phenolic (TPC), flavonoids (TFC) and anthocyanin (A). The six optimization objectives included simultaneous minimization of the quality parameters and energy consumption. The objective functions represent relationships between process variables and optimization objectives. The relations were approximated using an Artificial Neural Network (ANN). The Pareto optimal set with a nondominated sorting genetic algorithm was developed. No unequivocal solution to the optimization problem was found. Cannot be obtained *E. amoenum* petals characterized a low color change at low energy consumption due to its fluidized drying. Unique Pareto optimal solutions were found: $T_d = 54\text{ }^{\circ}\text{C}$ and $v_d = 1.0\text{ m/s}$ —for the strategy in which the lower losses of TAC, TFC and A are most important, and $T_d = 59.8\text{ }^{\circ}\text{C}$ and $v_d = 0.52\text{ m/s}$ —for the strategy in which the lower losses of TPC and TFC are important with accepted EC values. The results of this research are essential for the improvement of industrial dehydration of *E. amoenum* petals in order to maintain their high content of bioactive compounds with low energy consumption and low colour change

Keywords: artificial intelligence; drying; *Echium amoenum*; fluidization

1. Introduction

Many biochemical reactions in the body produce active oxygen species that are capable of destroying biomolecules [1]. The production of nitrogen oxide derivatives and forms of active oxygen is one of the causes of cancers and cardiovascular diseases [2]. Antioxidants are effective compounds that can prevent the oxidation of macromolecules such as proteins, nucleic acids and lipids [3]. These compounds trap free radicals and cause detoxification [4]. Some of these compounds are made with antioxidant or anti-oxidant properties as secondary metabolites of plants in nature, including compounds such as phenols, flavonoids, steroids, and terpenoids [5,6]. Dried petals of Borage Iranian (*Echium amoenum* Fisch. and C. A. Mey) contain considerably high amounts of phenol, flavonoids and anthocyanins [7] that play a major role in antioxidant activity [8]. For this reason, traditional medicine it is used as a drug for the treatment of depression [9], neurological problems [10–12], obsessive-compulsive disorder [10,13], anxiety [14], as an analgesic [15], for the prevention of inflammation and irritation of the kidneys and ducts, for rheumatism and heart disease [9], for colds, pneumonia, bronchitis [16,17], as a mucolytic drug, blood purifier, healer of soda

diseases [18,19], and due to its importance to the immune system [20], it is even recommended for the prevention of gastric cancer and diabetes [16,17].

The *E. amoenum* petals of the medicinal plant should be dried immediately and stirred to avoid microbial damage during drying. Improper processing and the use of inappropriate parameters for drying have negative effects on the therapeutic properties of pharmaceutical products [21]. Therefore, in energy-intensive processes such as drying, the key challenge is to find the most efficient way to produce a better-quality product with minimal energy consumption.

The fluidized bed drying (FBD) is a more attractive choice for drying medicinal plants [22,23] and to produce advanced functional materials such as nutrients, dietary supplements and herbal remedies [24,25] because of the intense mixing resulting in high heat and mass transfer rates as well as uniformity, which makes it possible to control the bed conditions even at temperatures causing thermal degradation [24,26]. This method is suitable for heat-sensitive foods aiming to retain the bioactive compound because it prevents overheating [24,27–29]. Due to their high drying efficiency, FBD is suitable for use in large-scale operations [30,31] and is typically an economical method compared to other drying techniques. Therefore, FBDs are cheaper, easier and more attractive for use in industry, and even for farmers to produce high-quality products [27].

Determining the optimal dehydration parameters is very important for solving the challenges in product quality and optimizing the amount of energy consumption for drying. However, there is little information in the literature about this subject. Balbay et al. [32] used ANNs to optimize the drying of Siirt pistachios. A backpropagation learning algorithm with Levenberg-Marguardt (LM) and scaled conjugate gradient and sigmoid transfer function in the network were used. The best LM algorithm had 15 neurons and the value of $R^2 = 99.99\%$ [32]. Feed Forward Neural Networks were used for modelling the nonlinear behavior of drying terebinth fruit, and was able to predict the optimal conditions for drying rate, energy consumption, moisture ratio and shrinkage [33]. A trained feedforward multilayer perceptron with back-propagation algorithm was able to predict the physicochemical properties of raspberries in a fluidized bed dryer [34].

Yüzgeç et al. [35] presented four models (modelling based on mass and heat transfer, modelling based on the mechanism of diffusion, ANN and ANFIS) to predict production performance and Baker's yeast temperature in the fluidized bed drying. It was found that the overall performance of the ANFIS model is better than the other three models [35]. Hashemi Shahraki et al. [36] performed the optimization of the fluidized bed drying of a sesame seed to find the least change in color and texture using the response surface method and genetic algorithm. The coefficients of Response Surface Methodology (RSM) models were optimized using the genetic algorithm (GA). GA-optimized models had better fitness than RSM models. [36]. Nazghelichi et al. [37] used the integration of RSM and GA to develop an ANN to optimize the FBD of the carrot. The results showed that this approach (RSM with GA) is a useful tool to find the optimal topology of ANN for predicting energy and exergy in FBD [37]. Amiri Chayjan et al. [38] predicted optimal drying conditions of pistachio for effective moisture diffusion, shrinkage, drying time, specific energy consumption, and color change as a function of fluidized bed drying conditions with RSM [38]. Tasirin et al. [39] used the Taguchi method to optimize the drying of bird's eye chilli in an FBD. They also obtained similar results when using the one factor at a time (OFAT) method [39].

Various methods such as mathematical modelling, regression analysis and ANN have been used to predict the drying rate. However, few studies have been conducted on the modelling of product quality parameters.

The tested product: *E. amoenum*, as mentioned, is a medicinal plant and the use of inappropriate parameters for drying have negative effects on the therapeutic properties of pharmaceutical dried products. It also requires, as with the case of any product, an appropriate colour of dried material. Drying is a very energy-consuming process, so it seems advisable to carry out this process with low energy expenditure. However, in the case of drying *E. amoenum* petals, where the quality directly

affects the price of the dried petals (and poor-quality product is worthless), the drying process should be carried out with the lowest possible energy expenditure.

The presented study investigated the effect of drying process variables (air temperature (T_d) and air velocity and (v_d)) on the following quality parameters of *E. amoenum* petals: the color difference and the bioactive compounds as loss of total antioxidant capacity, loss of total phenolic content, loss of total flavonoids content, anthocyanin loss and energy consumption for fluidized drying. The study focuses on multi-objective optimization (MOO) of the process variables. The goal in an MOO problem is to optimize the several objective functions simultaneously and thus finding the best parameters for *E. amoenum* petals drying process.

2. Materials and Methods

2.1. Material

Fresh *E. amoenum* petals were harvested in Afratape village, Golestan Province, Iran. The samples were collected every day and were kept in the refrigerator at 4 ± 0.5 °C before the beginning of the tests. The initial moisture content of the freshly harvested *E. amoenum* petals was about 8.67–10.29 d.b. and was reduced to the final moisture content about 0.058–0.041 d.b. at the end of the drying process for the safe storage.

2.2. Drying Process

To conduct experiments, a pilot-scale FBD was constructed in the Department of Agricultural Machinery Mechanics of Azadshahr University. FBD consists of three electric heaters, each of 800 W for heating air, a 1.5 kW fan for circulating air, a drying chamber with dimensions of $0.3 \times 0.3 \times 0.9$ m and a switchboard to control and regulate drying temperature (with accuracy ± 0.1 °C) and air velocity (with accuracy ± 0.1 m/s). The relative humidity of the drying air was about 35%. The size of its gas distribution chamber is approximately $0.25 \times 0.25 \times 0.3$ m, made with a stainless-steel plate of 1 mm thickness. A perforated distributor plate, with a thickness of 1 mm and holes of 3 mm in diameter, was firmly fixed to the bottom of the chamber.

At the beginning of each experiment, the air temperature and velocity were fixed when there was no sample in the FBD. To stabilize the drying conditions, the dryer was operated with no sample in the chamber for 30 min. The loading density of fresh *E. amoenum* petals was 1.4 kg/m^2 . More details of the device and the testing method can be found in previous research studies [40].

2.3. Quality Parameters

2.3.1. Color Measurement

Color preserving is crucial when processing food and herbs. Indeed, the first quality feature that a consumer notices when deciding to buy is product color. The machine vision was used to capture fresh and dried *E. amoenum* petals. The visual system consists of a black wooden box with dimensions of $50 \times 50 \times 50$ cm, four fluorescent lamps of 18 W located on the wall of the box at 45° for illumination, and a Sony Cyber-shot DSC-W370 digital camera with 14 Mpx of the resolution, which was placed vertically at a distance of 22.5 cm from the samples. Digital images were processed by MATLAB software in Lab color model to evaluate color changes. The color difference (CD) was calculated based on the following optimized formula by the CIE committee

$$CD = \sqrt{\left(\frac{\Delta L}{K_L S_L}\right)^2 + \left(\frac{\Delta C}{K_C S_C}\right)^2 + \left(\frac{\Delta H}{K_H S_H}\right)^2} \quad (1)$$

where ΔL , ΔC , ΔH are the differences in brightness, chroma, and hue angle of the dried sample from the reference (fresh) sample, respectively, K_L , K_C , K_H are the parameter factors that describe the effect

of the change from reference conditions (for reference conditions, they are all in 1), and S_L , S_C , S_H are the weighting functions ($S_L = 1$, $S_C = 1 + 0.045C$, and $S_H = 1 + 0.015C$).

2.3.2. Phytochemical Properties Measurement

Extract Preparation

Rufino et al. [41] procedure was used to prepare the extract. The dried sample was ground and passed through a sieve (40-mesh). A total of 2 g of sample powder was added to 4 mL of 50% ethanol (*v/v*). The mixture was mixed to homogenize it and was then kept at room temperature. After 1 h, the supernatant was transferred to a volumetric flask. A total of 4 mL of 70% acetone was added to the rest of the extract and homogenized using a mixer and kept at room temperature for 1 h. The obtained supernatant was transferred to the same flask containing the first supernatant and the solution volume was brought to 100 mL by distilled water and mixed well. Extraction was performed in triplicate for each treatment.

Determination of Antioxidant Activity by DPPH Method

To assess the antioxidant potential by DPPH free radical scavenging, changes in (DPHH) absorbance are examined. 1, 1-diphenyl-2-picrylhydrazyl (DPPH) is a stable free radical that can accept an electron or hydrogen molecule and become a neutral and stable molecule. DPPH has a strong absorption at a wavelength of 517 nm due to its odd electron; at this stage, the methanolic solution of DPPH is a deep purple color. In the presence of antioxidants, the odd electron can become an electron pair. Regarding the number of electrons received, absorption is reduced. At this stage, the color of the solution turns yellow/colorless. Using this absorption change, the ability of different compounds for free radical scavenging can be measured. The amount of change in the absorption of each sample depends on the ability of the radical adsorbent.

To determine the antioxidant activity, 1 mL of DPPH methanol solution (1 mM), was mixed with 3 mL of sample extract. The mixtures were maintained in a dark place at room temperature; after 30 min, the absorbance was read at 517 nm. The experiment was repeated three times for each sample solution. Antioxidant activity was calculated as the inhibition percentage was calculated by

$$\% \text{Inhibition} = 1 - \frac{A_{\text{sample}}}{A_{\text{control}}} \quad (2)$$

where A_{sample} is the absorbance of DPPH with the extracts and A_{control} is the absorbance of DPPH without the extracts.

Measurement of Total Phenolic Content (TPC)

The total phenol content (TPC) was determined using Folin-Ciocalteu assay by a UV/Vis spectrophotometer. A total of 10 mg/mL of the extract was mixed with 1 mL of Folin-Ciocalteu's reagent, and after 3 min, 0.8 mL of Na_2CO_3 (2%) was added, and then the volume was increased to 10 mL with water/methanol (4:6). After 30 min, the absorbance of the samples was measured at 740 nm. Tannic acid (0–800 mg/L) was used as the standard calibration curve, the TPC was reported to mg of tannic acid equivalent per gram of extract. The experiments were repeated in triplicate and their mean was reported.

Measurement Anthocyanin Content (A)

For determination of anthocyanins content (A), 0.1 g of the sample was soaked in 10 mL of acidified methanol (methanol/HCl = 99:1, *v/v*). The extract was maintained for 24 h in the dark at 25 °C. The extract was then centrifuged at 5000 rpm for 5 min. Absorption of the supernatant was measured at 550 nm.

Evaluation of Total Flavonoid Content (TFC)

The Dowd method, modified by Arvouet-Grand et al. [42], was used to measure the total amount of flavonoids. Briefly, in this method, 5 mL of 2% AlCl_3 in methanol was mixed with the same volume of aqueous extract. After 10 min, the absorbance of the extract solution and the blank solution (containing 5 mL of the extract with 5 mL of ethanol without AlCl_3 was read at 415 nm. Then, the total flavonoid content was determined using the quercetin standard curve (0–100 mg/L) and was expressed as mg of quercetin equivalent per gram of dry mass of petals.

Losses of phytochemical properties of *E. amoenum* petals were calculated as the percentage difference between the mentioned contents for dried (*d*) and fresh (*f*) materials according to the following formulas

$$A_{\text{loss}} = \frac{A_f - A_d}{A_f} \cdot 100\% \quad (3)$$

$$\text{TAC}_{\text{loss}} = \frac{\text{TAC}_f - \text{TAC}_d}{\text{TAC}_f} \cdot 100\% \quad (4)$$

$$\text{TFC}_{\text{loss}} = \frac{\text{TFC}_f - \text{TFC}_d}{\text{TFC}_f} \cdot 100\% \quad (5)$$

$$\text{TPC}_{\text{loss}} = \frac{\text{TPC}_f - \text{TPC}_d}{\text{TPC}_f} \cdot 100\% \quad (6)$$

2.4. Energy Consumption

The total energy consumption (EC) required for drying per kilogram of dried petals consists mainly of the thermal energy (E_{th}) needed to remove water from the crops, and the mechanical energy (E_{mec}) needed for the conveyance or airflow, which was calculated by [43]

$$E_{th} = A_{csa} v_a \rho_a C_a \Delta T t \quad (7)$$

where A_{csa} is the cross-section area (m^2), v_a is the dryer air velocity (m/s), ρ_a is the air density (kg/m^3), C_a is the air specific heat capacity ($\text{kJ}/(\text{kg}\cdot\text{K})$), ΔT is the temperature difference ($^\circ\text{C}$), t is the drying time (s).

The mechanical energy used for conveyance or airflow by a fan was calculated by [44]

$$E_{mec} = \Delta P v_a A_{csa} t \quad (8)$$

where ΔP is the pressure drop of the crop (Pa).

2.5. Objective Functions

Objective functions used by MOOGA algorithm represent relationships between T_d , v_d (process variables; drying air temperature: 40, 50, and 60°C , air flow velocity: 0.5, 0.75, and 1.0 m/s) and energy consumption (EC) for the drying process and quality characteristics of the dried material obtained (CD , A_{loss} , TAC_{loss} , TFC_{loss} , TPC_{loss}). Details about the used data are presented in Table 1.

The relations were approximated using ANN which topology is shown in Figure 1 (three-layer NN). The ANN task was to map input variables: T_d and v_d on to six outputs (CD , A_{loss} , TAC_{loss} , TFC_{loss} , TPC_{loss}) to obtain high correlation coefficient (R) and the lowest Mean Squared Error (MSE). The inputs and outputs of ANN were normalized (divide by maximum values, respectively) to obtain the range 0–1.

The actual values of the input variables were chosen randomly from a fixed set of data in each case. For this set of data, three levels of drying air temperature and three levels of air flow velocity were used (see Table 2). Seventy-three repetitions were performed for each level ($3 \cdot T_d \cdot 3 \cdot v_d$). A total of 657 different results was obtained.

Table 1. The statistics of data.

Data	Statistical Parameter		
	Mean $\pm$ SD (Range)	Coefficient of Variation	Skewness Coefficient
$A_{\text{loss}}, \%$	53.29 ± 9.84 (41.00–80.09)	0.19	1.35
CD _r	41.29 ± 7.92 (30.75–55.49)	0.19	0.26
EC, MJ/kg	654.92 ± 309.06 (266.39–1397.36)	0.47	1.11
TAC _{loss} , %	43.51 ± 15.55 (23.41–85.45)	0.36	1.44
TFC _{loss} , %	30.80 ± 19.00 (6.65–70.99)	0.62	0.98
TPC _{loss} , %	39.78 ± 11.31 (22.52–62.91)	0.28	0.10

Figure 1. The best Artificial Neural Network (ANN) structure.**Table 2.** Process variables and their bounds.

Item	Parameter	Unit	Factor Levels		
1	T_d	$^{\circ}\text{C}$	40	50	60
2	v_d	m/s	0.5	0.75	1

Chosen cases (657 cases from the experiments) were randomly divided into the following sets: 98 samples (15%), 461 samples (70%) for testing, and 98 samples (15%) for validation sets. The network used the default Lavenberg–Marquardt (L-M) algorithm for the training procedure. L-M locates the local minimum of a multivariate function, expressed as the sums of squares of several of non-linear, real-valued functions as demonstrated in paper [45]. In this study, the maximum number of epochs to train, the initial momentum and μ increase factor term were: 100, 0.4 and 10, respectively. The minimum value of MSE was always reached well within that number. The training process was repeated several times in order to obtain the best performance of ANN. All trials were implemented in MATLAB Neural Networks Toolbox R2018a. Moreover, the optimal experiment that minimizes the number of ANN models trained and validated and maximized the model accuracy has been done. The architecture of ANN parameters such as the number of neurons in the hidden layer, activate function in hidden and output layers and statistical values MSE and R were estimated in Table 3.

Table 3. Optimization of Artificial Neural Network (ANN) architecture.

Item	Activate Function in the Hidden Layer	Number of Neurons in the Hidden Layer	Activate Function in the Output Layer	Statistical Performance	
				MSE	R-Value
1	log-sigmoid	4	log-sigmoid	0.004546	0.9552
2	log-sigmoid	6	log-sigmoid	0.000844	0.9895
3	log-sigmoid	8	log-sigmoid	0.000292	0.9922
4	log-sigmoid	4	pureline	0.006726	0.9428
5	log-sigmoid	6	pureline	0.001043	0.9903
6	log-sigmoid	8	pureline	0.000684	0.9915
7	Tansig	4	pureline	0.005523	0.9472
8	Tansig	6	pureline	0.000888	0.9897
9	Tansig	8	pureline	0.000792	0.9914
10	Tansig	4	log-sigmoid	0.003880	0.9672
11	Tansig	6	log-sigmoid	0.000765	0.9908
12	Tansig	8	log-sigmoid	0.000741	0.9911

It can be seen from Table 3, the lowest MSE = 0.000292 and high R-value = 0.9922 for Item 3 was obtained.

2.6. Multi-Objective Optimization Problem

The MOO task consisted in the determination of the set of optimal conditions of the drying process. All the functions were minimalized (EC, CD, A_{loss} , TAC_{loss} , TFC_{loss} , TPC_{loss}) subject to constraints on the process variables (drying parameters: T_d , v_d). Equation (9) presents the mentioned MOO problem.

$$\min(x) = \begin{cases} \min EC(T_d, v_d) \\ \min CD(T_d, v_d) \\ \min A_{loss}(T_d, v_d) \\ \min TAC_{loss}(T_d, v_d) \\ \min TFC_{loss}(T_d, v_d) \\ \min TPC_{loss}(T_d, v_d) \\ 40\text{ }^{\circ}\text{C} \leq T_d \leq 60\text{ }^{\circ}\text{C} \\ 0.5\text{ m/s} \leq v_d \leq 1.0\text{ m/s} \end{cases} \quad (9)$$

The Pareto front for this multiobjective optimization problem was generated using a nondominated sorting genetic algorithm (NSGA II). The algorithm was implemented in MATLAB Global Optimization Toolbox R2018a. Subsequent steps of this algorithm are presented, i.e., in [46]. The genetic algorithm parameters are shown in Table 4.

Table 4. The Nondominated Sorting Genetic Algorithm (NSGA II) parameters.

Population Type	Double Vector
Crossover function	Intermediate
Crossover rate	85%
Migration	Forward
Mutation function	Uniform
Mutation rate	15%
Number of generations	300 × number of variables
Pareto front population fraction	0.8
Population size	20-number of variables
Selection function	Tournament size = 2

3. Results and Discussion

3.1. Data

The statistics of the used data are presented in Table 1.

3.2. Objective Functions

To approximate functional relations between air drying temperature, drying air velocity (T_d and v_d) and energy consumption drying and quality parameters (CD, A_{loss} , TAC_{loss} , TFC_{loss} , TPC_{loss}) of dried *E. amoenum* petals, different ANN structures (with various transfer functions) were tested. Considering the lowest MSE, the best result (MSE = 0.00029) was obtained for the ANN structure which consisted of eight nodes in the hidden layer (see Figure 1, Table 2).

The hidden and output layers of the best ANN structure processed data with a log-sigmoid transfer function both in output and hidden layers, respectively, as demonstrated in Figure 1 (see Table 3, Item 3). The ANN training phase was stopped at the 21st iteration as shown in Figure 2. It can be seen that test set error and validation error have similar characteristics. The following final MSE values were obtained: 0.00075, 0.00029, 0.0021 for training, validation and test sets, respectively. Therefore, the final mean-square error is small. Linear regression between the network outputs and the corresponding

targets is shown in Figure 3. The following R: 0.9933, 0.9974, and 0.9818 for training, validation and test sets, respectively, indicated that data from the ANN were in agreement with the experimental data. Finally, the R-value is over 0.99 for the total response (see Figure 3).

Figure 2. Changes in the MSE calculated for the following sets: test, training and validation.

Figure 3. The ANN goodness of fit.

The ANN training phase was stopped at the 21st iteration (Figure 2). The following final MSE values were obtained: 0.00075, 0.00029, 0.0021 for training, validation and test sets, respectively. The R of 0.9933, 0.9974, and 0.9818 for training, validation and test sets, respectively, indicated that data from the ANN were in agreement with the experimental data (Figure 3). The hidden and output layers of the best ANN structure processed data with a log-sigmoid transfer function (Figure 1).

The energy consumption for drying process was determined with the following formula (from ANN, taking into account multiplication by EC_{max})

$$EC = \frac{1397.4}{1 + \exp^{-(0.05334880F_1 - 7.57453800F_2 + 1.26911235F_3 + 1.04827174F_4 + 7.17002195F_5 + 1.13226411F_6 - 4.87949849F_7 - 3.95034501F_8 - 0.14950873)}} \quad (10)$$

whereas quality parameters of dried petals from formulas (from ANN, taking into account multiplication by the appropriate quality parameters maximum values)

$$TAC_{loss} = \frac{85.45}{1 + \exp^{-(0.91486229F_1 + 7.21271787F_2 - 3.52344619F_3 - 0.16353038F_4 - 2.01802500F_5 - 6.806017979F_6 + 1.64711850F_7 - 6.54342140F_8 + 9.20950911)}} \quad (11)$$

$$TFC_{loss} = \frac{71}{1 + \exp^{-(2.24787236F_1 - 2.48837154F_2 + 0.55347643F_3 - 0.02646887F_4 + 6.63595873F_5 - 1.85385629F_6 - 9.33823416F_7 - 2.20003463F_8 + 5.83514537)}} \quad (12)$$

$$A_{loss} = \frac{80.1}{1 + \exp^{-(2.30683301F_1 - 0.77573645F_2 + 2.30807532F_3 - 1.19423933F_4 - 2.98162470F_5 + 1.45621634F_6 - 1.05510991F_7 - 0.33137939F_8 + 0.83477706)}} \quad (13)$$

$$TPC_{loss} = \frac{62.91}{1 + \exp^{-(6.93202597F_1 + 7.73183587F_2 + 2.78498679F_3 - 1.34403737F_4 - 4.36853377F_5 + 3.60560168F_6 - 0.09079078F_7 + 1.05068213F_8 - 5.30369243)}} \quad (14)$$

$$CD = \frac{42.69}{1 + \exp^{-(5.21780748F_1 + 1.06399550F_2 + 1.47336382F_3 - 3.27940014F_4 - 6.22372789F_5 + 0.37476380F_6 + 3.14566334F_7 + 0.81603238F_8 - 1.22684000)}} \quad (15)$$

where $F_{(i=1 \div 8)}$ from

$$F_i = \frac{1}{1 + \exp^{-W_i}} \quad (16)$$

W_1 – W_5 from

$$W_i = \frac{1}{1 + \exp^{-(D_{i1}T_d/60 + D_{i2}v_d + D_{i3})}} \quad (17)$$

and D_{ji} are shown in Table 5.

Table 5. Constants (weights and biases) D_{ij} in Equation (17).

i	D_{i1}	D_{i2}	D_{i3}
1	−35.560371	1.530375	35.746782
2	5.264209	−34.088544	9.816984
3	22.479106	−27.444875	6.052853
4	−17.140856	−32.840889	30.725816
5	21.678617	31.658204	−31.391203
6	−23.550824	28.269281	−7.366114
7	39.790524	16.976584	−38.393101
8	28.398313	−24.399395	1.949355

Equations (10)–(15) (respected normalization) were used for algorithm (Equation (9)).

The validation of the model (ANN) using the validation set and, additionally, all data, to demonstrate the reliability of predicted values was conducted. The R for validation and all data was 0.9974 and 0.9922 (Figure 3), whereas mean square errors (MSE) were 0.00026 and 0.00029, respectively. This confirms the accuracy and consistency of the proposed model.

3.3. Multi-Objective Optimization

The MOO problem formulated in Equation (9) was solved with the genetic algorithm using the initial population size of 40. Table 3 shows the controlled parameters of NSGA II. The optimization problem converged to the Pareto optimum set after 146 genetic algorithm generations. In the study, the probability of mutation and crossover and were 0.15 and 0.85, respectively. One hundred and eighty design points formed Pareto set given in Table A1. Figure A1 presents the impact of T_d and v_d on EC, CD, and quality parameters (A_{loss} , TAC_{loss} , TFC_{loss} , TPC_{loss}) of the *Echium amoenum* petals (data from Table A1).

Figure 4 shows the Pareto fronts for EC and CD, A_{loss} , TAC_{loss} , TFC_{loss} , TPC_{loss} , respectively.

The smallest values of EC were obtained for ID134, ID132, and ID131 (278.3, 288.8, and 295.5 MJ/kg, respectively). It corresponds to the following drying parameters: $T_d = 60.00$ °C and $v_d = 0.50$ m/s, $T_d = 59.84$ °C and $v_d = 0.50$ m/s, $T_d = 59.77$ °C and $v_d = 0.50$ m/s, respectively. However, due to the very small differences between the individual values of drying parameters obtained and the lack of such precise settings, it can be assumed that the best parameters due to energy savings are the following: $T_d = 60$ °C and $v_d = 0.5$ m/s. Assuming that the temperature and velocity of the drying air can be set (in the dryer) with an accuracy of 0.5 °C and 0.02 m/s, drying at $T_d = 60.0 \pm 0.5$ °C and $v_d = 0.5 \pm 0.02$ m/s allows for obtaining *Echium amoenum* petals with the following parameters: TAC_{loss} , TFC_{loss} , A_{loss} , TPC_{loss} , CD, EC: 45.5%, 28.0%, 47.3%, 29.8%, 36.7, and 328.8 MJ/kg, respectively (average values for mentioned ranges of T_d and v_d).

Figure 4. Pareto fronts—two-dimensional views: (a) EC-TAC_{loss}, (b) EC-CD, (c) EC-TFC_{loss}, (d) EC-A_{loss}, (e) EC-TPC_{loss}; O—the best solutions, +—data, ■—EC_{min}, ■—TAC_{loss} min, ▲—TFC_{loss} min, ▼—A_{loss} min, ▲—TPC_{loss} min, ▲—CD_{min}.

However, additionally taking into account the quality parameters of the obtained dried material, it should be noted that these solutions (as mentioned above, for EC_{min}-ID134, ID132, and ID131) CD are 36.16, 36.65 and 36.87, respectively, and they are very different from CD_{min} = 19 (1.90, 1.93, and 1.94 times higher, respectively). Thus, the dried petals obtained at low-energy expenditure (long drying time) are characterized by significant petal color changes (large CD) (see Figure 4b).

Pareto front (Figure 4b) indicates the following solutions: ID70, ID75 and ID84, for which EC is 835.6, 804.8, and 766.4 MJ/kg, respectively, and CD are 30.7, 31.6, and 31.8, respectively. These solutions are obtained for the following drying process parameters: air drying temperature 44.47, 45.42, and 45.41 °C, and air-drying velocity 0.50, 0.51, and 0.50 m/s. However, due to the very small differences between each value of T_d and v_d obtained and the inability to set these parameters so precisely (adjustment by 0.02 °C and 0.01 m/s), it can be assumed that the best parameters due to the simultaneous energy-saving and color preservation are the following: $T_d = 45.5$ °C and $v_d = 0.5$ m/s. However, for these solutions, EC, CD, A_{loss} , TAC_{loss} , TFC_{loss} , TPC_{loss} are respectively about 2.9, 1.7, 1.7, 2.2, 8.6, and 2.5 times higher than their minimum values. CD was always conflicting with other quality parameters (see Figure 4b). Assuming that the temperature and velocity of the drying air can be set (in the dryer) with an accuracy of 0.5 °C and 0.02 m/s, drying at $T_d = 45.5 \pm 0.5$ °C and $v_d = 0.5 \pm 0.02$ m/s allows for obtaining *Echium amoenum* petals with the following parameters: TAC_{loss} , TFC_{loss} , A_{loss} , TPC_{loss} , CD, EC: 36.6%, 43.3%, 60.0%, 47.9%, 33.6, and 702.3 MJ/kg, respectively (average values for mentioned ranges of T_d and v_d).

Dried petals with low A, TAC, TFC and TPC losses also cannot be obtained with the least energy expenditure. For the obtained solutions (for EC_{min}), A_{loss} , TAC_{loss} , TFC_{loss} and TPC_{loss} are as follows: for ID134: 45.7%, 49.4%, 27.5%, 30.8%, for ID132: 46.6%, 48.9%, 27.1%, 32.2%, and for ID131: 47.1%, 48.5%, 26.9%, 32.7%, respectively. Therefore, these values are about 1.2, 3.1, 4.0, and 1.5 times higher than the lowest values, respectively, whereas for $A_{loss min}$, $TAC_{loss min}$, $TFC_{loss min}$, and $TPC_{loss min}$, the energy consumption is 434.8 (ID92: $T_d = 53.94$ °C, $v_d = 1.00$ m/s), 1344.3 (ID1: $T_d = 40.00$ °C, $v_d = 0.60$ m/s), 666.3 (ID 26: $T_d = 50.59$ °C, $v_d = 1.00$ m/s) and 507.5 MJ/kg (ID62: $T_d = 60.00$ °C, $v_d = 0.58$ m/s), respectively.

For TAC_{loss} Pareto front (Figure 4a) indicates solutions ID54, ID55 and ID69, for which EC is 526.0, 520.2, and 456.2 MJ/kg, while TAC_{loss} is 31.9, 32.0, and 33.2%, respectively. These solutions are obtained for the following drying process parameters: air drying temperature 59.94, 60.00, and 53.35 °C, and air-drying velocity 0.65, 0.61, and 1.00 m/s. However, for these solutions, EC is 1.9, 1.9, and 1.6, CD 2.0, A_{loss} is 1.3, 1.3, and 1.0, TAC_{loss} is 4.5, 4.6, and 2.1, TFC_{loss} is 4.6, 4.6, and 1.26, and TPC_{loss} 1.1, 1.0, and 1.8 times higher than their minimum values. Therefore, ID69 is better than ID54 and ID55 from the EC, A_{loss} , TAC_{loss} , and TFC_{loss} point of view. Assuming the mentioned accuracy of T_d and v_d setting, drying at $T_d = 53.5 \pm 0.5$ °C and $v_d = 1.0 \pm 0.02$ m/s (parameters from ID 69) allows for obtaining *Echium amoenum* petals with the following parameters: TAC_{loss} , TFC_{loss} , A_{loss} , TPC_{loss} , CD, EC: 35.0%, 9.0%, 39.1%, 37.7%, 38.3, and 445.5 MJ/kg, respectively (average values for mentioned ranges of T_d and v_d).

For A_{loss} Pareto front (Figure 4d), solutions are indicated for ID134 and ID116, for which EC is 278.2, and 410.3 MJ/kg, while A_{loss} is 45.7 and 39.6%, respectively. These solutions are obtained for the following drying process parameters: air drying temperature 60.00 and 55.12 °C, and air-drying velocity 0.50 and 1.00 m/s. However, for these solutions, EC is 1.0 and 1.5, CD is 1.9 and 2.0, A_{loss} is 1.2 and 1.0, TAC_{loss} is 3.2 and 2.8, TFC_{loss} is 4.0 and 1.7, and TPC_{loss} is 1.5 and 1.7 times higher than their minimum values. Therefore, ID116 is better than ID134 from the TFC_{loss} point of view. Assuming the mentioned accuracy of T_d and v_d setting, drying at $T_d = 55.0 \pm 0.5$ °C and $v_d = 1.0 \pm 0.02$ m/s (parameters from ID 134) allows for obtaining *Echium amoenum* petals with the following parameters: TAC_{loss} , TFC_{loss} , A_{loss} , TPC_{loss} , CD, EC: 35.8%, 10.2%, 42.1%, 40.4%, 38.1, and 499.4 MJ/kg, respectively (average values for mentioned ranges of T_d and v_d).

For TFC_{loss} Pareto front (Figure 4c) solutions for ID69 ($TFC_{loss} = 8.6\%$ and $EC = 456.2$), ID 92 ($TFC_{loss} = 9.4\%$ and $EC = 434.8$), ID109 ($TFC_{loss} = 10.3\%$ and $EC = 420.2$ MJ/kg), and ID116 ($TFC = 11.3\%$ and $EC = 410.3$ MJ/kg) are indicated. These solutions are obtained for the following drying process parameters: air drying temperature 53.35, 53.94, 54.51 and 55.12 °C, and air-drying velocity 1.00 m/s. However, for these solutions, EC is 1.6, 1.6, 1.5 and 1.5, CD is 2.0, A_{loss} is 1.0, TAC_{loss} is 2.1, 2.4, 2.6 and 2.8, TFC_{loss} is 1.3, 1.4, 1.5 and 1.7, and TPC_{loss} is 1.8, 1.8, 1.7 and 1.7 times higher than its minimum values. Assuming the mentioned accuracy of T_d and v_d setting, drying at $T_d = 53.5 \pm 0.5$ °C and

$v_d = 1.0 \pm 0.02$ m/s (parameters from IDs: 69, 109—those are better from the TAC_{loss} and TFC_{loss} point of view) allows for obtaining *Echium amoenum* petals with the following parameters: TAC_{loss} , TFC_{loss} , A_{loss} , TPC_{loss} , CD, EC: 35.0%, 9.0%, 39.1%, 39.1%, 38.3, and 445.5 MJ/kg, respectively (average values for mentioned ranges of T_d and v_d).

For TPC_{loss} Pareto front (Figure 4e) indicates solutions ID94 ($TPC_{loss} = 25.2\%$ and $EC = 445.5$ MJ/kg), ID107 ($TPC_{loss} = 26.0\%$ and $EC = 410.1$ MJ/kg), ID 117 ($TPC_{loss} = 27.0\%$ and $EC = 348.6$ MJ/kg) and ID113 ($TPC_{loss} = 27.6\%$ and $EC = 364.9$ MJ/kg). These solutions are obtained for the following drying process parameters: air-drying temperature 59.76, 59.82, 59.98 and 59.86 °C, and air-drying velocity 0.54, 0.53, 0.51 and 0.52 m/s, respectively. However, for these solutions, EC is 1.6, 1.5, 1.3 and 1.3, CD is 2.0, 2.0, 1.9 and 1.9, A_{loss} is 1.3, 1.3, 1.2 and 1.2, TAC_{loss} is 2.4, 2.5, 2.8 and 2.7, TFC_{loss} is 4.4, 4.3, 4.2 and 4.2, and TPC_{loss} is 1.2, 1.2, 1.3 and 1.3 times higher than their minimum values. Due to the very small differences between the individual values of drying parameters obtained and the lack of such precise settings, it can be assumed that the best parameters due to energy savings are following: $T_d = 60.0$ °C and $v_d = 0.52$ m/s. Assuming the mentioned accuracy of T_d and v_d setting, drying at $T_d = 60.0 \pm 0.5$ °C and $v_d = 0.52 \pm 0.02$ m/s can obtain *Echium amoenum* petals with the following parameters: TAC_{loss} , TFC_{loss} , A_{loss} , TPC_{loss} , CD, EC: 44.0%, 28.3%, 47.7.1%, 29.0%, 36.8, and 349.1 MJ/kg, respectively (average values for mentioned ranges of T_d and v_d).

It can be stated that there is no unequivocal solution to the optimization problem written by Equation (9). The solutions relate to the *Echium amoenum* petals drying parameters at which the lowest values of individual quality parameters, EC or CD, sometimes groups of the parameters were obtained. However, CD was always conflicting with other quality parameters (see Figure 4b), so this parameter was omitted in further considerations.

The optimization results show (Figures 5 and 6) that A, TAC, TFC are interrelated.

Figure 6 shows the four solutions for the optimization task. The ID92 is characterized by $EC = 434.8$ MJ/kg (1.6 times higher than EC_{min}), whereas $A_{loss} = 39.0$ (the lowest of all obtained optimization solutions), $TAC_{loss} = 36.8\%$ (2.4 times higher than $TAC_{loss min}$), $TFC_{loss} = 9.4\%$ (1.4 times higher than $TFC_{loss min}$), and TPC_{loss} is 37.0% (1.4 times higher than $TPC_{loss min}$) ($CD = 38.3$ —2.2 times higher than CD_{min}). The parameters of the drying process for ID92 are the following: $T_d = 53.94$ °C and $v_d = 1.00$ m/s. The ID109 solution differs only in value of T_d (T_d is 0.57 °C higher than for ID92 and amounts to 54.51 °C ($v_d = 1.00$ m/s). For this solution, EC is a little lower (420 MJ/kg), but TAC_{loss} is higher (40.1%).

The next ID107 solution ($EC = 410.1$ MJ/kg) is characterized by the lowest of the four solutions $TPC_{loss} = 26.0\%$ (1.2 times higher than $TPC_{loss min}$). For this solution, TAC_{loss} is higher than for the previously mentioned ID92 and lower than ID109 ($TAC_{loss} = 39.2\%$ —2.5 times higher than $TAC_{loss min}$), but TFC_{loss} and A_{loss} are already much bigger: $TFC_{loss} = 29.6\%$ (4.3 times higher than $TFC_{loss min}$), and $A_{loss} = 48.7\%$ (1.3 times higher than $A_{loss min}$), CD is high and amount 37%. The parameters of the drying process for ID107 are the following: $T_d = 59.82$ °C and $v_d = 0.53$ m/s. A similar solution is ID111 for which EC, TFC_{loss} , A_{loss} are lower and amount to 381.3 MJ/kg, 29.1%, 48.12%, while TAC_{loss} and TPC_{loss} are larger (41.2% and 27.0%, respectively); CD is high: 36.9%. The parameters of the drying process for ID111 are very similar to ID107 and amount: $T_d = 59.85$ °C and $v_d = 0.52$ m/s. For this solution, EC is little lower (381.3 MJ/kg), but TAC_{loss} and TPC_{loss} are higher (41.2 and 27.0%, respectively).

Figure 6 shows Pareto fronts for EC and, simultaneously, A_{loss} , TAC_{loss} , TFC_{loss} , and TPC_{loss} .

Considering the maximum values of $TAC_{loss max} = 80.5\%$, $TFC_{loss max} = 70.9\%$, $A_{loss max} = 76.9\%$, and $TPC_{loss max} = 60.6\%$, it can be assumed that for the four indicated solutions, the losses do not differ significantly and are much smaller than the mentioned maximum losses.

However, where the quality of the dried product directly affects the price (poor-quality product is worthless), the drying process should be carried out with the acceptable (not always the lowest) energy expenditure. For the strategy in which, apart from EC minimization, the lower losses of TAC, TFC and A are most important, while accepting quite high TPC_{loss} and high CD, the drying parameters of *E. amoenum* petals are the following: $T_d = 54.0$ °C and $v_d = 1.0$ m/s. Assuming the

mentioned accuracy of T_d and v_d setting, drying at $T_d = 54.0 \pm 0.5$ °C and $v_d = 1.0 \pm 0.02$ m/s can obtain *Echium amoenum* petals with the following parameters: TAC_{loss} , TFC_{loss} , A_{loss} , TPC_{loss} , CD, EC: 36.8%, 9.4%, 39.0%, 38.3%, 37.1, and 434.9 MJ/kg, respectively (average values for mentioned ranges of T_d and v_d). However, when apart from EC minimization, low losses of TPC and TFC are important; with losses of TAC and CD similar to those mentioned previously, the drying parameters of *E. amoenum* petals are the following: $T_d = 59.8$ °C and $v_d = 0.53$ m/s. Assuming the mentioned accuracy of T_d and v_d setting, drying at $T_d = 60.0 \pm 0.5$ °C and $v_d = 0.52 \pm 0.02$ m/s can obtain *Echium amoenum* petals with the following parameters: TAC_{loss} , TFC_{loss} , A_{loss} , TPC_{loss} , CD, EC: 44.0%, 28.3%, 47.7%, 29.0%, 36.8, and 349.1 MJ/kg, respectively (average values for mentioned ranges of T_d and v_d).

Jafarian et al. [47] optimized a counter-flow indirect dew-point evaporative cooler precise model. In an MOO task, the NSGA II is often used. NSGA II has commonly been used to understand a wide range of problems such as a heating, cooling, and power system integrated with biomass gasification [48,49], waste heat recovery systems [50] and organic Rankine cycle [51]. Moreover, the NSGA II algorithm was widely used in the food industry for the determination of Biot mass number [52] and the mass diffusion coefficient [53] in the drying process. Winiczenko et al. [54,55] successfully applied the algorithm to the rehydration process.

Figure 5. Pareto fronts-two-dimensional views: (a) TFC_{loss} - TAC_{loss} , (b) A_{loss} - TFC_{loss} , (c) A_{loss} - TAC_{loss} ; +—data, ■— EC_{loss} min, ■— TAC_{loss} min, ▲— TFC_{loss} min, ▼— A_{loss} min, ▼— TPC_{loss} min, ▼— CD min.

Figure 6. Pareto fronts-two-dimensional views: (a) EC-TAC_{loss}-TFC_{loss}, (b) EC-A_{loss}-TPC_{loss}; O—the best solutions, +—data.

4. Conclusions

The effect of T_d (40–60 °C) and v_d (0.5–1 m/s) in fluidized drying on the energy consumption and the quality parameters (TAC_{loss}, TPC_{loss}, TFC_{loss} and A_{loss}) of *E. amoenum* petals was studied. A novel multi-objective optimization (MOO) algorithm, based on Pareto optimization, genetic algorithm (GA) and artificial neural network (ANN), was developed. The following optimization objectives of A_{loss}, CD, EC, TAC_{loss}, TFC_{loss} and TPC_{loss} were used for its simultaneous minimization. The objective functions were developed by using ANN. The Pareto optimal set was developed with the non-dominated sorting genetic algorithm II.

It can be stated that there is no unequivocal solution to the optimization problem. The quality of dried *E. amoenum* petals directly affects the price of the dried flakes (and poor-quality product is worthless). Therefore, the drying process does not have to be carried out with the lowest energy consumed, but only with the low possible energy expenditure.

Cannot be obtained *E. amoenum* petals characterized a low color change at low energy expenditure for fluidized drying.

The smallest value of energy consumption (EC = 278.3 MJ/kg) was obtained for the following drying parameters: $T_d = 60.0$ °C and $v_d = 0.50$ m/s.

The following solutions were obtained considering the simultaneous minimization of EC and loss of: A (and low TFC_{loss}) $T_d = 55.0$ °C, $v_d = 1.0$ m/s, TAC and TFC $T_d = 53.4$ °C, $v_d = 1.0$ m/s, TPC $T_d = 60.0$ °C, $v_d = 0.52$ m/s, CD $T_d = 45.5$ °C, $v_d = 0.5$ m/s.

A unique Pareto optimal solution was found at $T_d = 54\text{ }^{\circ}\text{C}$ and $v_d = 1.0\text{ m/s}$ —for the strategy in which the lower losses of TAC, TFC and A are most important at the accepted EC value, resulting in 36.8%, 9.4%, 39.0%, 434.9 MJ/kg, 37.1%, 38.3 for TAC_{loss}, TFC_{loss}, A_{loss}, EC, TPC_{loss}, and CD, respectively.

The next unique Pareto optimal solution was found at $T_d = 59.8\text{ }^{\circ}\text{C}$ and $v_d = 0.52\text{ m/s}$ —for the strategy in which, the lower losses of TPC and TFC are important at accepted EC values, resulting in 44.0%, 28.3%, 47.7%, 349.1 MJ/kg, 29.0%, 36.8 for TAC_{loss}, TFC_{loss}, A_{loss}, EC, TPC_{loss}, and CD respectively.

The results of this research are essential for the improvement in the industrial dehydration of *E. amoenum* petals to maintain their high content of bioactive compounds with low energy consumption and low colour change.

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Appendix A

Table A1. Pareto optimal set.

ID	T_d ($^{\circ}\text{C}$)	v_d (m/s)	TAC _{loss} (%)	TFC _{loss} (%)	A _{loss} (%)	EC (MJ/kg)	TPC _{loss} (%)	CD (-)
1	40.000	0.6028	15.5858	70.8745	68.7699	1344.28	46.1350	21.0011
2	40.000	0.6001	15.6012	70.8748	68.8430	1343.89	46.2663	20.6208
3	40.134	0.6064	15.7583	70.8605	68.5418	1342.17	45.9180	22.0248
4	40.221	0.5851	16.1691	70.8504	69.1502	1335.38	47.1364	19.5874
5	40.000	0.5788	16.5041	70.8493	69.8209	1330.07	48.2291	19.0219
6	40.888	0.6071	17.1377	70.7215	67.5978	1321.18	45.5829	25.4078
7	40.859	0.5708	17.3711	70.7689	69.0575	1316.73	47.7881	20.0681
8	40.964	0.5633	18.0330	70.7329	69.4783	1304.84	48.6995	20.1816
9	40.802	0.5564	18.8029	70.7086	70.4593	1288.28	50.3152	20.5535
10	41.721	0.5531	19.5171	70.5514	68.9342	1276.96	48.8205	21.4891
11	42.091	0.5887	19.6477	70.2024	66.0556	1272.02	45.2829	27.6331
12	40.577	0.5463	20.5847	70.6162	72.0233	1241.84	52.9722	22.5080
13	40.553	0.5438	21.1197	70.5796	72.3701	1225.79	53.5775	23.1716
14	42.144	0.5423	21.1422	70.3358	69.1900	1239.82	49.9232	22.6491
15	41.589	0.5386	21.4824	70.4404	70.9708	1224.87	52.1253	22.9470
16	42.807	0.5490	21.6218	69.9080	66.7102	1230.98	47.2828	24.2905
17	41.660	0.5344	22.2704	70.3605	71.3702	1201.61	52.8887	23.7347
18	43.173	0.5614	22.3986	69.1387	64.7806	1206.82	45.4343	27.6069
19	43.297	0.5570	22.7985	68.9722	64.7386	1196.69	45.6191	27.4233
20	42.452	0.5300	23.3083	70.0258	70.0803	1179.22	51.8709	24.3546
21	40.615	0.5330	23.5134	70.3661	73.5354	1143.12	55.6526	26.0738
22	43.252	0.5359	23.7092	69.3147	66.9747	1175.00	48.6325	25.2399
23	41.406	0.5278	23.8769	70.2442	72.7607	1142.02	54.9546	25.7457
24	41.162	0.5278	24.1238	70.2500	73.2173	1128.20	55.5052	26.2727
25	42.813	0.5269	24.2144	69.7217	69.5615	1154.61	51.6737	25.0430
26	50.591	0.9999	24.5102	6.84569	41.9597	666.275	44.9053	37.4724
27	40.481	0.5273	25.2813	70.1761	74.3836	1066.89	56.9869	28.2821
28	41.649	0.5214	25.3363	70.0328	73.1127	1089.76	55.7523	27.1048
29	40.268	0.5260	26.0489	70.0881	74.8092	1027.36	57.5725	29.3358
30	41.493	0.5181	26.4113	69.9193	73.8011	1040.44	56.7117	28.4200
31	49.749	0.9860	26.7558	7.12927	41.9010	675.647	44.4061	37.4590
32	43.919	0.5239	26.8407	67.6590	66.5582	1076.45	49.6296	27.2909

Table A1. Cont.

ID	T_d (°C)	v_d (m/s)	TAC _{loss} (%)	TFC _{loss} (%)	A _{loss} (%)	EC (MJ/kg)	TPC _{loss} (%)	CD (-)
33	42.630	0.5144	26.9370	69.4720	71.9537	1049.71	55.0790	27.5885
34	43.245	0.5159	27.0288	68.9459	70.0725	1060.92	53.2611	27.1378
35	43.111	0.5139	27.3586	69.0393	70.7779	1045.18	54.0670	27.4946
36	44.638	0.5436	27.7207	62.7990	61.9428	1028.16	45.1789	31.3429
37	44.323	0.5234	28.0671	65.9500	65.2116	1033.29	48.8051	28.4362
38	44.078	0.5172	28.3639	66.9800	67.1126	1023.14	50.8391	28.0583
39	44.401	0.5220	28.4895	65.5307	65.1426	1018.22	48.9286	28.6694
40	41.243	0.5114	28.8391	69.5810	74.9239	920.616	58.2657	31.0604
41	45.028	0.5403	29.2165	59.2599	61.0678	967.715	45.0479	32.3714
42	44.913	0.5284	29.4566	61.5194	62.4430	973.776	46.6515	30.6108
43	40.556	0.5124	29.6740	69.4811	75.6816	855.236	59.0421	32.5339
44	45.149	0.5341	29.8902	58.5777	61.1454	946.937	45.5170	32.0171
45	44.473	0.5140	30.0455	65.0186	66.2225	962.562	50.6645	29.1488
46	45.284	0.5661	30.3912	51.2274	60.0866	875.445	44.3100	36.7234
47	44.722	0.5161	30.4066	63.4119	64.9155	948.113	49.5622	29.6542
48	44.760	0.5154	30.6353	63.1196	64.8806	939.589	49.6288	29.7694
49	43.769	0.5045	30.8322	67.3715	70.4261	921.979	54.8267	29.5713
50	40.793	0.5062	31.3291	69.1400	75.9172	781.205	59.4893	33.5674
51	45.604	0.5688	31.4580	46.2762	59.6851	817.464	44.3646	37.6547
52	45.782	0.5644	31.8243	44.9343	59.3789	804.178	44.2784	37.5585
53	44.838	0.5104	31.8570	62.3900	65.4709	894.793	50.7025	30.1863
54	59.941	0.6518	31.9310	31.0738	50.8695	526.021	22.7013	37.6509
55	60.000	0.6115	31.9469	31.6509	50.0663	520.214	21.2203	37.2300
56	45.782	0.5331	32.0650	50.4278	59.4735	848.728	44.9372	33.9206
57	43.700	0.5000	32.1938	67.2148	71.4045	864.085	56.0519	30.5423
58	45.087	0.5122	32.2700	60.1736	64.1653	877.199	49.6670	30.6848
59	45.960	0.5401	32.3050	47.0179	58.8761	822.488	44.3654	35.2275
60	46.010	0.5425	32.3841	45.9620	58.7633	813.481	44.2534	35.6436
61	45.922	0.5330	32.5086	48.4669	59.1390	827.981	44.8301	34.2934
62	59.999	0.5821	32.5624	31.7383	49.5725	507.509	20.9404	37.0085
63	40.251	0.5055	32.5827	68.8473	76.4657	697.505	60.0583	34.9319
64	45.524	0.5186	32.6326	55.0583	61.5357	852.724	47.3451	31.9131
65	40.765	0.5023	32.7415	68.8262	76.2224	711.395	59.9114	34.5437
66	59.680	0.5939	32.8222	30.4087	51.2409	515.148	24.3646	37.8991
67	45.759	0.5218	32.9667	51.7326	60.3665	831.444	46.3713	32.7629
68	46.290	0.5402	33.2192	42.5454	58.2868	776.855	44.2263	36.0174
69	53.349	1.0000	33.2257	8.60094	39.1274	456.219	38.4671	38.1894
70	44.469	0.5009	33.3552	64.3361	68.7220	835.616	54.1281	30.6962
71	46.381	0.5335	33.7758	42.1080	58.1531	765.606	44.4871	35.4775
72	46.289	0.5299	33.7780	43.6502	58.4139	774.659	44.8008	34.8860
73	59.841	0.5637	33.8146	30.9301	49.9328	491.492	22.8749	37.3018
74	46.437	0.5311	34.0835	41.5876	58.0821	756.977	44.6133	35.3431
75	45.424	0.5083	34.1712	56.2996	63.5236	804.760	49.9078	31.5912
76	40.255	0.5000	34.4667	68.3615	76.7749	609.041	60.4905	35.9966
77	59.099	0.5722	34.5130	28.2904	53.1085	503.679	30.0839	38.8465
78	40.161	0.5000	34.6309	68.3050	76.8392	597.709	60.5489	36.1576
79	59.973	0.5508	34.7398	31.2630	48.9291	471.406	21.9331	36.8246
80	45.564	0.5074	34.8147	54.4744	63.1152	779.902	49.8239	31.9246
81	40.000	0.5000	34.9154	68.2019	76.9444	578.368	60.6444	36.4260
82	59.794	0.5513	35.0108	30.5053	49.8079	473.530	23.8691	37.3249
83	45.702	0.5076	35.2064	52.6205	62.5324	763.706	49.4808	32.2149
84	45.409	0.5036	35.2697	56.2343	64.4647	766.372	51.1901	31.8008
85	46.288	0.5163	35.3186	44.2816	59.2547	739.745	46.5377	33.7303
86	46.700	0.5242	35.3628	38.6027	57.7125	715.622	45.0214	35.2261
87	46.033	0.5113	35.4529	47.9701	60.6969	746.255	47.9488	32.9478

Table A1. Cont.

ID	T_d (°C)	v_d (m/s)	TAC _{loss} (%)	TFC _{loss} (%)	A _{loss} (%)	EC (MJ/kg)	TPC _{loss} (%)	CD (-)
88	59.879	0.5452	35.6059	30.6939	49.2019	461.112	23.3175	37.0443
89	46.825	0.5242	35.6568	37.0966	57.4609	701.996	44.9338	35.4718
90	46.318	0.5140	35.7858	43.8369	59.3950	725.441	46.9174	33.6733
91	58.880	0.5512	36.3600	27.2964	53.3569	479.777	32.6907	39.0414
92	53.939	1.0000	36.7557	9.39434	39.0208	434.842	36.9683	38.3352
93	46.214	0.5073	36.8255	45.1165	60.6016	698.199	48.5288	33.2768
94	59.763	0.5382	36.8879	29.9447	49.4814	445.508	25.1815	37.2906
95	46.958	0.5143	37.3581	35.3654	57.5611	657.082	46.0526	34.9500
96	47.226	0.5173	37.4271	32.6200	56.8453	644.409	45.3970	35.6154
97	59.708	0.5343	37.6947	29.5376	49.5717	435.388	26.2064	37.3959
98	59.113	0.5364	38.1019	27.4990	52.0843	447.379	31.8769	38.6070
99	46.859	0.5090	38.1658	36.1990	58.2353	639.575	47.1164	34.5085
100	48.672	0.5258	38.3068	24.1953	55.6542	575.447	44.5490	38.0699
101	46.562	0.5051	38.3141	39.8437	59.6512	643.887	48.4268	33.9083
102	46.624	0.5051	38.4785	38.9629	59.4319	637.482	48.3202	34.0153
103	46.982	0.5079	38.7019	34.5880	57.9816	621.470	47.1781	34.6711
104	47.045	0.5079	38.8427	33.8518	57.8027	615.947	47.0963	34.7710
105	58.968	0.5322	39.0621	26.8445	52.4079	437.302	33.6279	38.7930
106	48.810	0.5204	39.1500	23.3134	55.2566	559.828	44.7873	37.8055
107	59.816	0.5268	39.2046	29.5511	48.6925	410.084	26.0331	37.0406
108	47.256	0.5061	39.7098	31.3221	57.3671	587.809	47.1865	35.0257
109	54.508	1.0000	40.0664	10.2798	39.1615	420.183	35.6689	38.4790
110	48.577	0.5117	40.4615	23.1311	54.9428	542.093	45.4546	36.9439
111	59.844	0.5195	41.2409	29.1232	48.1230	381.308	27.0237	36.8839
112	58.039	0.5215	42.1880	23.9532	54.3615	414.195	41.1841	39.6514
113	59.860	0.5158	42.4534	28.8611	47.7969	364.905	27.6420	36.7969
114	58.945	0.5175	42.8107	25.7902	51.6970	386.419	36.1783	38.6917
115	59.841	0.5143	43.0324	28.6368	47.7761	358.066	28.2115	36.8297
116	55.116	1.0000	43.1670	11.3378	39.5858	410.292	34.5031	38.6324
117	59.976	0.5128	43.4414	29.0487	46.9871	348.594	27.0568	36.4174
118	59.561	0.5136	43.6132	27.4655	49.0314	359.252	31.4166	37.5287
119	59.728	1.0000	43.6925	22.8926	45.1382	449.982	25.0679	38.1739
120	59.856	0.5122	43.8052	28.4865	47.5463	347.847	28.5651	36.7621
121	45.875	0.8931	45.2709	10.4006	40.1815	555.382	37.3554	38.0971
122	59.158	1.0000	45.3964	20.9157	45.1683	440.309	27.7278	38.6335
123	44.563	0.8879	45.4699	10.0605	40.8465	661.976	38.9996	37.6515
124	51.609	0.5000	45.7376	17.8572	53.5657	432.356	47.6500	38.4335
125	45.259	0.8875	45.8463	10.4058	40.3297	583.888	37.6486	37.9806
126	60	0.5057	46.4558	28.3297	46.2691	311.418	28.8048	36.2478
127	45.579	0.8863	46.5858	10.7442	40.2284	550.463	36.9306	38.1536
128	59.999	0.5039	47.3473	28.0837	46.0996	301.162	29.4200	36.2231
129	59.596	0.5041	47.5954	26.5108	48.0828	309.954	33.7648	37.3234
130	58.669	0.5044	47.9450	23.7058	51.5452	328.681	41.2854	38.8813
131	59.764	0.5021	48.4520	26.8800	47.1033	295.467	32.6772	36.8740
132	59.841	0.5012	48.8544	27.0555	46.6381	288.801	32.1621	36.6514
133	56.387	0.5000	49.2614	19.8441	54.6667	349.268	49.0778	39.8969
134	60.000	0.5000	49.4027	27.5199	45.6965	278.242	30.8390	36.1600
135	57.204	0.5000	49.7252	20.6144	53.9997	333.247	47.9628	39.7597
136	42.813	0.8725	50.1373	11.0467	41.9201	796.301	39.7337	37.1548
137	42.688	0.8725	50.5409	11.1310	42.1006	815.967	39.9327	37.0784
138	43.193	0.8554	51.3762	12.1084	40.7913	630.871	36.6778	37.8667
139	42.215	0.8598	52.2223	12.1541	41.8650	795.187	38.8742	37.1293
140	43.073	0.8492	52.2998	12.6920	40.8526	612.876	36.1078	37.9802
141	41.902	0.8442	53.7151	13.7760	41.5134	738.529	37.1919	37.3385

Table A1. Cont.

ID	T_d (°C)	v_d (m/s)	TAC _{loss} (%)	TFC _{loss} (%)	A _{loss} (%)	EC (MJ/kg)	TPC _{loss} (%)	CD (-)
142	41.898	0.8338	54.5485	15.0577	41.4416	680.287	35.9118	37.6340
143	40.029	0.7876	54.7425	41.2993	45.9544	884.387	34.3823	36.0081
144	42.330	0.8154	55.1864	17.5144	42.8762	570.405	34.5823	38.5146
145	41.797	0.8054	55.4097	20.4765	43.6637	604.704	34.5449	38.3638
146	41.225	0.8542	55.4434	14.2039	43.0684	923.723	39.6268	36.4880
147	41.403	0.8664	55.9242	13.1669	43.7443	981.324	40.9211	36.3234
148	40.507	0.8116	56.2913	25.2199	43.1649	819.550	35.3048	36.6127
149	40.545	0.8365	56.6608	18.8091	43.2491	933.584	38.2381	36.1543
150	41.164	0.8641	56.8806	13.8508	43.9995	1004.67	40.9338	36.1734
151	40.820	0.8579	57.7335	15.2446	44.1617	1020.57	40.6202	35.9904
152	42.029	0.8944	57.8736	11.9453	45.2191	1082.63	43.0325	36.0160
153	40.764	0.8596	58.3146	15.3538	44.4235	1041.20	40.8816	35.8890
154	40.015	0.8389	58.5608	21.9292	44.6049	1053.31	39.3423	35.3033
155	41.103	0.8724	58.8645	13.8301	44.8631	1069.93	41.8600	35.8994
156	40.264	0.8481	58.8845	18.7420	44.6186	1057.34	40.1442	35.5276
157	43.220	0.9306	60.0827	11.5561	46.5592	1155.83	44.5017	35.7222
158	40.393	0.8619	60.8652	16.8524	45.4152	1113.21	41.4841	35.4126
159	40.127	0.8594	61.8278	18.4751	45.8224	1139.80	41.4885	35.1183
160	40.507	0.8741	63.1968	15.9313	46.1929	1160.10	42.4115	35.2690
161	42.058	0.9140	63.9741	12.7639	46.8656	1185.91	43.9841	35.4766
162	40.731	0.8848	64.6624	15.0846	46.6353	1183.50	42.9724	35.2405
163	40.564	0.8844	65.6333	15.6985	46.9008	1198.46	42.9984	35.0921
164	40.569	0.8920	67.7084	15.8189	47.4562	1225.94	43.3209	34.9230
165	40.444	0.8920	68.4482	16.2952	47.6604	1235.77	43.3310	34.8078
166	40.033	0.8848	68.8889	18.0805	47.8874	1246.28	43.1227	34.5286
167	41.783	0.9250	69.3261	14.0605	47.9984	1245.94	44.1387	35.0084
168	41.769	0.9272	69.9927	14.2335	48.1457	1252.72	44.1503	34.9467
169	41.718	0.9295	70.8740	14.4986	48.3361	1261.32	44.1458	34.8611
170	41.508	0.9276	71.5386	14.8512	48.4590	1267.28	44.0755	34.7810
171	41.904	0.9413	72.6955	14.9051	48.7758	1279.00	44.2026	34.6910
172	40.138	0.9126	74.3338	17.9720	49.2147	1297.14	43.6576	34.1689
173	41.516	0.9470	75.2540	16.0395	49.3469	1301.10	44.0190	34.3856
174	41.150	0.9432	75.8196	16.5507	49.4815	1306.05	43.9144	34.2808
175	41.736	0.9608	76.5284	16.4527	49.6767	1311.89	43.9728	34.2412
176	41.141	0.9557	77.3241	17.1872	49.8796	1318.63	43.8126	34.0876
177	40.694	0.9701	79.0754	18.4062	50.3985	1333.24	43.5631	33.7820
178	40.000	0.9687	79.6255	19.3879	50.6419	1338.86	43.4302	33.5853
179	40.000	1.0000	80.4607	19.5847	50.8631	1344.63	43.2752	33.4946
180	40.000	1.0000	80.4607	19.5847	50.8631	1344.63	43.2752	33.4946

Figure A1. The impact of T_d and v_a on: (a) EC, (b) CD, and quality parameters (c) A_{loss} , (d) TAC_{loss} , (e) TFC_{loss} , (f) TPC_{loss} of the *Echiium amoenum* petals.

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