Application Of High Electric Field (HEF) In Drying: A Review

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High electric field (HEF) drying is a novel non-thermal method wherein either alternating current (AC) or direct current (DC) high voltages can be used for moisture evaporation during drying. Multiple point-to-plate electrode systems are efficient in accelerating drying of fruit and vegetables and present significant prospects for bulk drying. It results in food products of superior quality in terms of their physiochemical properties like shrinkage, color, flavor and nutrient content. Given their simplicity of design and lesser energy consumption, compared to oven- and freeze-drying systems, HEF drying systems show great potential in the drying industry.

Key Words: High electric field (HEF), Air ions, Drying, Non-thermal drying, Corona Current.

1. Introduction

Drying is the oldest method of food preservation. Conventional drying techniques are associated with convective, conductive, and radiative heating of the food material. Alterations in the physical, chemical and biological properties of foods may occur when conventional drying techniques are applied. Microwave drying also generates heat. Freeze-drying produces a high quality processed food products but is very costly. Recent market trends indicate that consumers demand superior quality (natural color, flavor and full nutrient complement) in high value foods of a seasonal and perishable nature, in nutraceuticals, baby foods, herbs, dried foods for the outdoors, and instant meals. Thus, there exists a demand for an alternate method of drying foods with minimum adverse effects on their natural qualities.

High electric field (HEF) drying is a lesser known new method of non-thermal drying. Under HEF-drying, electric fields of high intensity and normal frequency (60 Hz) are applied to generate ionized forms of air-constituent gases within the foodstuff (Hashinaga et al., 1999). The movement of these air ions in a strong electric field generates an ionic wind, which in turn impinges upon water molecules in the food, producing a turbulent vortex-like motion which finally results in evaporation. Given their dipolar nature, water molecules in the substance undergoing drying can be expected to orient themselves in the direction of electric field, creating order (i.e., reducing entropy). As the release of heat is associated with a lowering of entropy, the temperature of the material undergoing drying is also lowered. Therefore, the thermodynamic processes to consider regarding the lowering of temperatures under HEF are the rapid rate of evaporation and the exothermic interaction of electric and dielectric fields.

When such air ions are applied to microorganisms, corona effects were shown to ensue during the evaporative process (Krueger et al., 1958). Evaporation phenomena of air ions with water, saline solutions, ethyl alcohol and n-heptane have been studied (Hart & Bachman, 1968). Drying of potato (*Solanum tuberosum* L.) slabs was carried out with air ions from corona discharge using standard frequency (60 Hz) HEF (Cheng & Barthakur, 1991; 1994). Employing various strengths of

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electric field to dry paper towel, Carlon & Latham (1992) observed that an increase in field strength increased the drying rate. Similarly, Shigemitsu et al., (1994) showed the evaporation rate of distilled water to be directly proportional to discharge potential. While air temperature and humidity had no effect on the drying of radish (*Raphanus sativus* L.) in a corona discharge, increased air flow-through during HEF drying decreased the drying rate (Xue et al., 1994). Isobe et al., (1999) observed accelerated drying and enhanced sublimation of agar gel under a DC-powered HEF-generating system.

The evaporative effects of standard frequency HEF were found to be directly proportional to the electric field strength and the duration of its application, but inversely proportional to electrode gap or head distance, i.e., the distance between the surface of the material undergoing drying (resting on the grounded metallic plate or mesh) and the bent metal wire or needle-tip electrode connected to the high voltage generator. A two-pointed electrode design under an optimized electrode gap (head distance) allowed faster drying of an apple (*Malus sylvestris* Mill.) slice than did a single-pointed electrode system (Hashinaga et al., 1999). Bajgai & Hashinaga (2001a; b) studied drying rate and final quality of radish and spinach (*Spinacia oleracea* L.) dried under an optimized AC-generated multi-point to plate electrode HEF system. Drying rates obtained under the multi-needle emitting electrode system were as high as those achieved by oven drying. The Hunter color, as well as the chlorophyll, ascorbic acid, organic acid and sugar contents of the HEF-dried spinach were greater than those of oven-dried spinach. The HEF-dried radish slices also showed better color, less shrinkage, greater water absorption and less loss of solids in rehydration than oven-dried radish slices.

Barthakur & Arnold (1995) showed the evaporation rate of water due to negative air ions to be greater than that associated with positive air ions. They postulated that the greater ion current and ionic wind velocity were responsible for the faster evaporation rate. Lai & Wong (2003) showed HEF drying with either the negative or positive corona to vary linearly with the strength of the electric field applied. Energy loss in corona discharge while drying of agricultural materials was found to be smaller than the conventional drying techniques (Lai & Wong, 2003; Xue et al., 1994).

The non-thermal nature of HEF-drying may present a wide range of applications in industrial drying, given its capacity to produce high quality processed products (Bajgai & Hashinaga, 2001a). This paper seeks to review the scope and prospects of HEF drying, considering the need for new technologies of non-thermal processing of biological materials.

2. Principles of High Electric Field Drying

Interactions between air ions, water molecules and solid particles in the presence of a HEF are complex. The ionization process produces free electrons and positively charged atoms or molecules such as O+, O2+, N+ and N2+. Within 10-8 to 10-7 seconds after their liberation, free electrons combine with un-ionized molecular oxygen to form O2-. At 0°C and 0.1 kPa pressure the molecular ions collide approximately 5 x 109 times per sec. During these collisions the monomolecular ions form into molecular clusters resulting in a kernel molecule to which several water molecules attaches themselves. Small multimolecular air ions are cluster of molecules bound together by Coulomb forces resulting from their excesses or deficiencies of electrons (Bracken, 1987). In HEF drying, ions are accelerated from the ion emitting electrode to the negative electrode resulting in an ionic wind. The total force of such ions is (Sigmond, 1982):

$$F = Ed + e_0/2\ [\nabla(E^2\ \rho\ \delta k/\delta\rho) - E^2\nabla k] \qquad (1)$$

where,

F is the force of the ions (N m^{-3})

E is the strength of the electric field (V m^{-1}),

d is the charge density (C m^{-3}),
e_0 is the permittivity of free space (F m^{-1}),
∇ is the vector gradient operator,
ρ is the mass density of air (kg m^{-3}),
k is the relative dielectric constant (unitless)

The velocity of air ions, v, can be calculated as:

$$v = (e_0\,\rho)^{1/2}E \qquad (2)$$

The velocity of the electric wind can be increased until the breakdown voltage is attained. The breakdown voltage depends upon the conditions of the medium where the electric field is applied. Generally, HEF drying is carried out with silent discharge of air ions.

The distribution of unipolar space-charge-dominated corona current, I_s, which is the maximum possible unipolar ion current or unipolar saturation current is approximated as:

$$I_S \approx (2\mu\varepsilon_0 V^2)/l \qquad (3)$$

where,

μ is the mobility of unipolar ion in a gas in combined space-charge flow conditions ($m^2\,V^{-1}\,s^{-1}$)
ε_0 is the permittivity of electric field strength F m^{-1}),
V is the voltage applied (kV), and
l is the distance between the pointed electrode and the grounded plate (m)

3. HEF Drying Methods

High electric field drying consists of point electrode and a ground metallic plate or mesh on which the material to be dried is placed. The point electrode is connected to a transformer producing high DC or AC voltage. The high voltage transformer is connected to a voltage regulator. The voltage regulator is supplied from a 60 Hz, 110 V, AC supply. The voltage required for HEF drying can be set with the regulator. Headspace distance or electrode gap can be fixed by moving the pointed electrode up and down. Figure 1 illustrates a HEF drying set-up designed for drying a radish slice (Bajgai & Hashinaga, 2001a).

Under HEF drying the greater the voltage applied the greater is the drying rate. However voltages are maintained below those causing electrode to electrode arcing. Optimum electrode gap and sharpness of the corona-generating needle are also important for faster drying. Voltages applied in various HEF drying studies and resulting ionic currents are presented in Table 1.

4. Discussion

4.1 Drying rate

Figure 2 shows a comparison of drying rate under HEF, oven and ambient air drying processes. The greater drying rate for HEF drying with multiple needles under ambient conditions (25°C and 65% RH) demonstrates the effectiveness of HEF drying compared to oven drying (at 60°C) or ambient drying (Bajgai & Hashinaga, 2001 a). Lai and Wong (2003) studied electric field-enhanced drying at ambient condition and with airflow. Under ambient conditions the applied voltage until the occurance of sparking is directly proportional to the applied voltage, but at high airflow velocities sparking was independent of the applied voltage, due to inertial forces. Barthakur & Arnold (1995) showed ionic current and electric wind velocities to be greater for negative air ions than for positive air ions. Under electrode gaps of 5, 10 and 20 mm and an applied voltage of 5.25 kV the electric wind velocities for negative air ions were 2.5, 1.7 and 0.8 m s^{-1}, respectively, whereas for the positive air ions they were 2.1, 1.5 and 0.7 m s^{-1}, respectively. Under these same conditions ionic currents for the negative and positive air ions were 16.2, 7.8 and 2.4µA and 9.0, 5.0 and 1.9 µA, respectively.

Electric field strength, electrode gap, sharpness of the electrode and the inter-electrode separation are the determinant factors for HEF drying. Hashinaga et al., (1999) observed maximum drying under a 13 mm electrode gap. The optimum electric fields for sharp and blunt needles were 4.4×10^5 and 4.7×10^5 V m^{-1}, respectively. After the introduction of a certain number of pointed electrodes for a fixed drying area, the rate of drying did not increase with the addition of further pointed electrodes, indicating the importance of inter-electrode separation (Bajgai & Hashinaga, 2001a). In some studies, instead of a needle electrode, wire electrodes were used to study drying. Hashinaga et al. (1995) used a wire electrode to evaporate water and alcohol. Wire electrodes are blunt at their ion emitting ends whereas needle electrodes are sharper. More studies on the drying characteristics of wire and needle electrode-equipped HEF drying systems are needed to understand their influence on the mechanisms of HEF drying.

Both AC and DC high voltages are employed in HEF drying. Hashinaga et al., (1995) found AC high voltages to be more effective in evaporating water than positive or negative high DC voltages. Xue et al., (1994), Hashinaga et al., (1999) and Bajgai and Hashinaga (2001a,b) applied high AC voltages for evaporation and drying. Direct current high voltages were used in drying by Shigemitsu et al. (1994), Cheng and Barthakur (1994), Isobe et al. (1999) and Lai and Wong (2003). However further studies on AC and DC high voltages would be required to fully assess the superior HEF drying protocol.

4.2 Quality of HEF dried food

New technologies are driven by the demands of the modem market for higher nutrient content, natural color, texture and flavor of foodstuffs. Food quality is considered as one of the main preoccupations in food research. However, there are few reports available on the effect of HEF drying on food quality.

The drying of fruits and vegetables always produces a considerable shrinkage effect due to their high initial moisture content. It is directly related to the water volume removed during the process (Kechaou & Roques, 1989). Shrinkages of a radish slice after 7 hours of HEF-drying (25°C) or oven-drying (60°C), were 50% and 80%, respectively (Bajgai & Hashinaga, 2001a). Similar results were obtained by Hashinaga et al. (1999) for apple slices. Excessive shrinkage during oven-drying may be associated with heat damage of cell walls and membrane. The greater reduction of shrinkage under HEF-drying represents the retention of natural structure of the biological material. Water absorption and rehydration of HEF- and oven-dried radish slices at ambient temperature (25°C) are compared in Figures 4 and 5. HEF-dried radish slices showed greater water absorption and rehydration ratios compared to oven-dried slices.

The reduced absorption of water and rehydration ratio in oven-dried material is associated with a collapse in structure and reduction in porosity (Rahman, 2001). Greater shrinkage also affects aroma retention, caking and stickiness, puffiness and final moisture content of the freeze dried materials (Bellows & King, 1973).

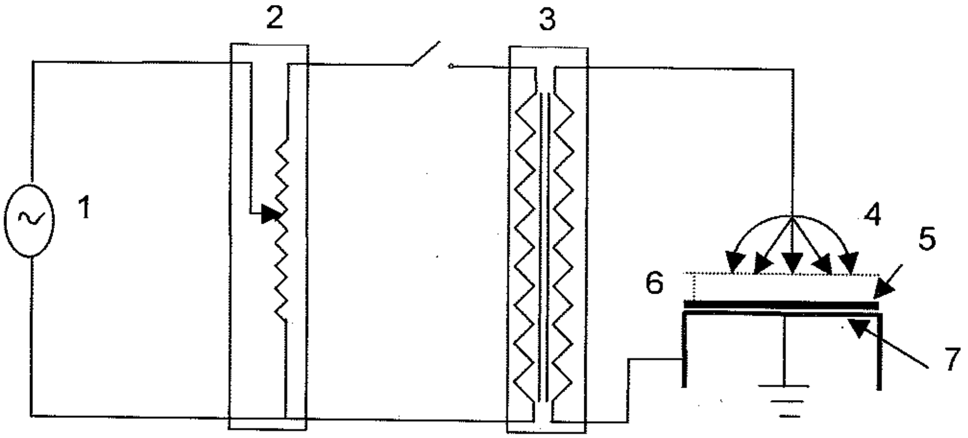
Deterioration of color during drying of agricultural products is important not only in terms of eye appeal but also in terms of interactions between its color components and important nutrients like vitamins. Table 1 shows that the Hunter 'a' color values of spinach (the more negative represents more green) after 7 hours of HEF- and ambient air drying were closer to initial values and most altered in the oven-dried samples (Bajgai & Hashinaga, 2001b). Total chlorophyll, chlorophyll *a*, chlorophyll *b* and ascorbic acid were higher in HEF-dried than the oven-dried spinach (Bajgai & Hashinaga, 2001b). In a different study, HEF-dried radish showed less solid loss during soaking, greater water absorption and better color than the oven-dried radish (Bajgai & Hashinaga, 2001a). In yet another study, HEF-dried apple slices did not show any observable product degradation, extensive color change or formation of foreign substances (Hashinaga et al., 1999). HPLC analysis was carried out for organic acids and sugars in HEF and oven-dried samples (Figs. 6 and 7). They showed identical peaks for organic acids, indicating that HEF drying did not generate any substances not generated under oven drying (Bajgai & Hashinaga, 2001b).

4.3 Costs of HEF drying

The theoretical concept for current-voltage relationship (Eq. 3) and the currents measured in various HEF-drying studies (Table 2) showed the existing ionic current under HEF drying to be small in magnitude, in the range of µA or mA. Although, the voltage applied (*E*) remains fairly high, the power equation, $P = EI$ indicates that with a small value of current, *I*, the consumption of electrical energy will be very little during the drying process. The Townsend effect of secondary charge generation which amplifies the charges between the pointed and the plate electrode has made this an inherently energy-efficient method (Chen & Barthakur, 1994). Energy dissipation during high voltage generation requires attention in terms of the modification of old-type generators. However, the electrical power used in HEF-drying is very small compared to oven- and freeze-drying techniques (Lai & Wong, 2003, Flink, 1977). The cheaper cost of the HEF drying apparatus, with a simple needle and plate assembly and the convenience of its use at room temperature and normal atmospheric pressures, may make it very popular.

5. Conclusions

High electric field-drying is a new non-thermal method of drying with the potential to be applied to the bulk drying of high value agricultural products. HEF-drying produces superior quality food products. This method of drying is energy efficient, whereas conventional drying methods are energy intensive. However, more research on energy dissipation, post-dried food quality and scale-up related problems is needed.



1. Alternating current 100 V, 2. Voltage regulator, 3. Step up transformer, 4. Multi point electrode, 5. Headspace distance, 6. Drying material, 7. Copper mesh electrod

Figure 1: *Schematic diagram of high electric field (HEF) drying*

Table 1: *Hunter color value 'a' for HEF (25°C), oven (60°C) and ambient air-dried (25°C) spinach*

Drying methods	Drying time (h)			
	0	3	5	7
HEF	-19.2±1.4	-17.5±1.4	16.9±1.3	15.7±1.4
Oven	-19.2±1.4	-16.5±1.4	13.0±1.4	-7.6±1.3
Ambient air	-19.2±1.4	-17.4±1.3	16.9±1.2	-15.2±1.4

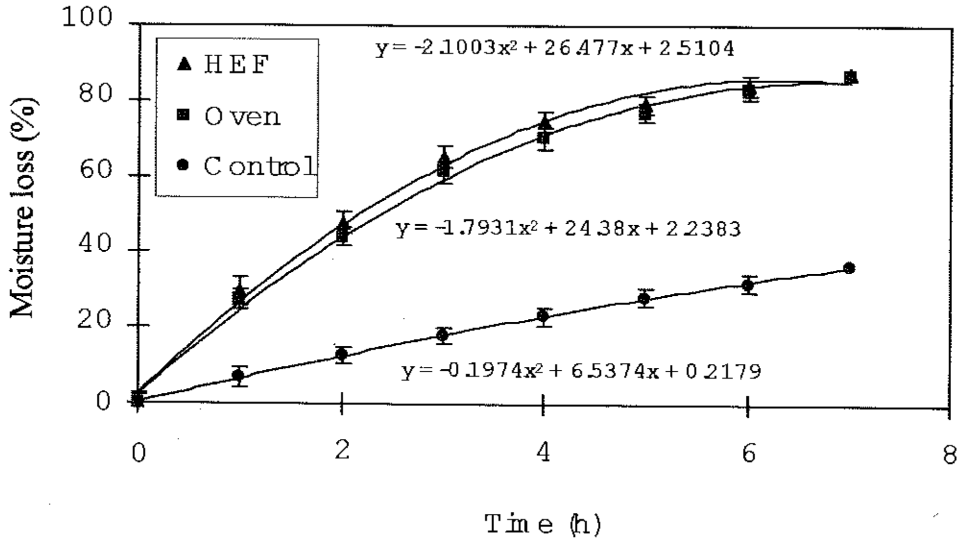


Figure 2: *HEF-, oven- and ambient air-drying pattern of radish slices*

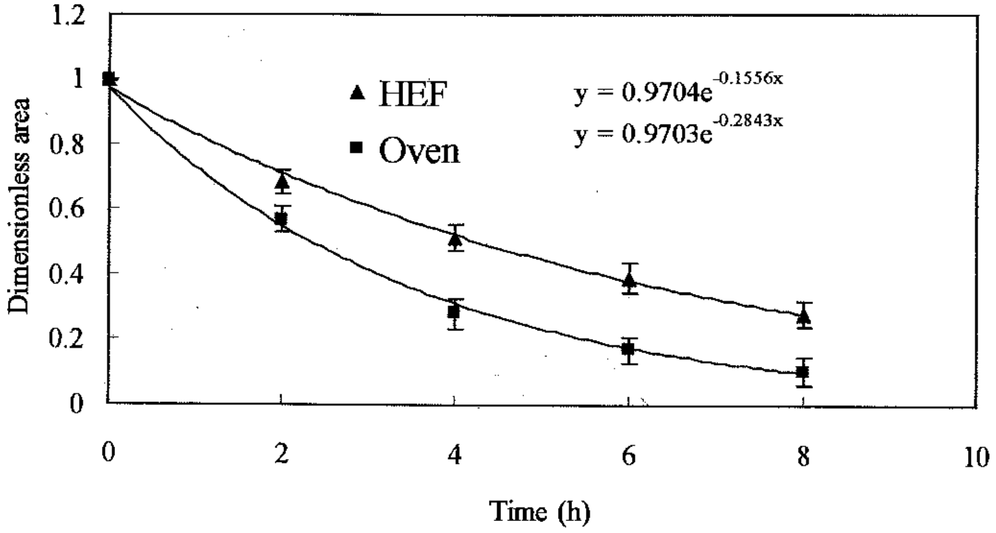


Figure 3: *Pattern of shrinkage for HEF- and oven-dried radish slices*

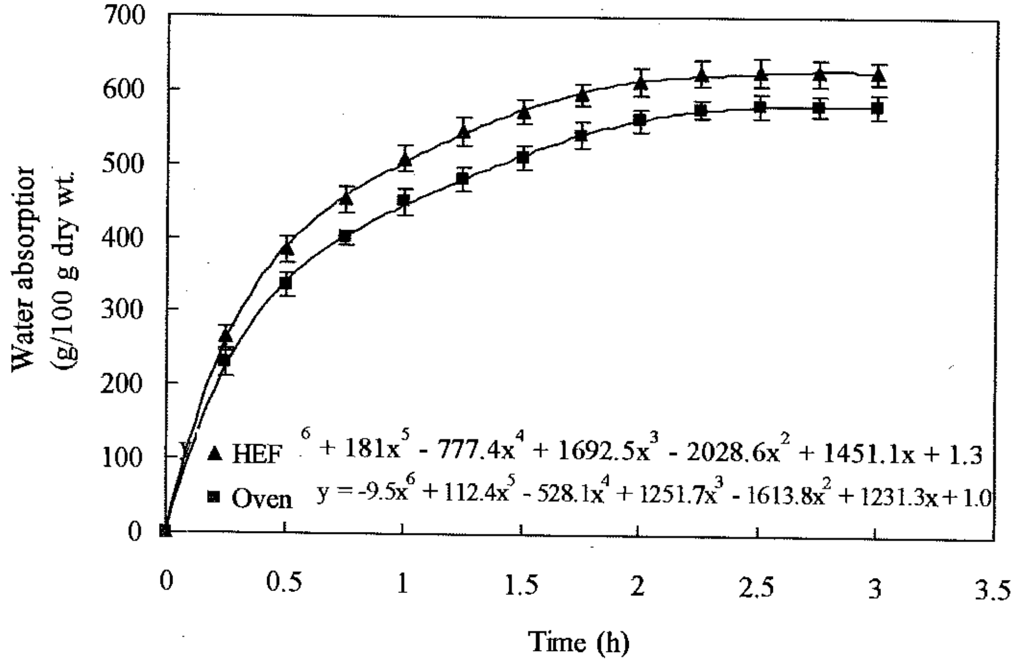


Figure 4: *Water absorption of radish slices dried with HEF (25°C) and oven (60°C)*

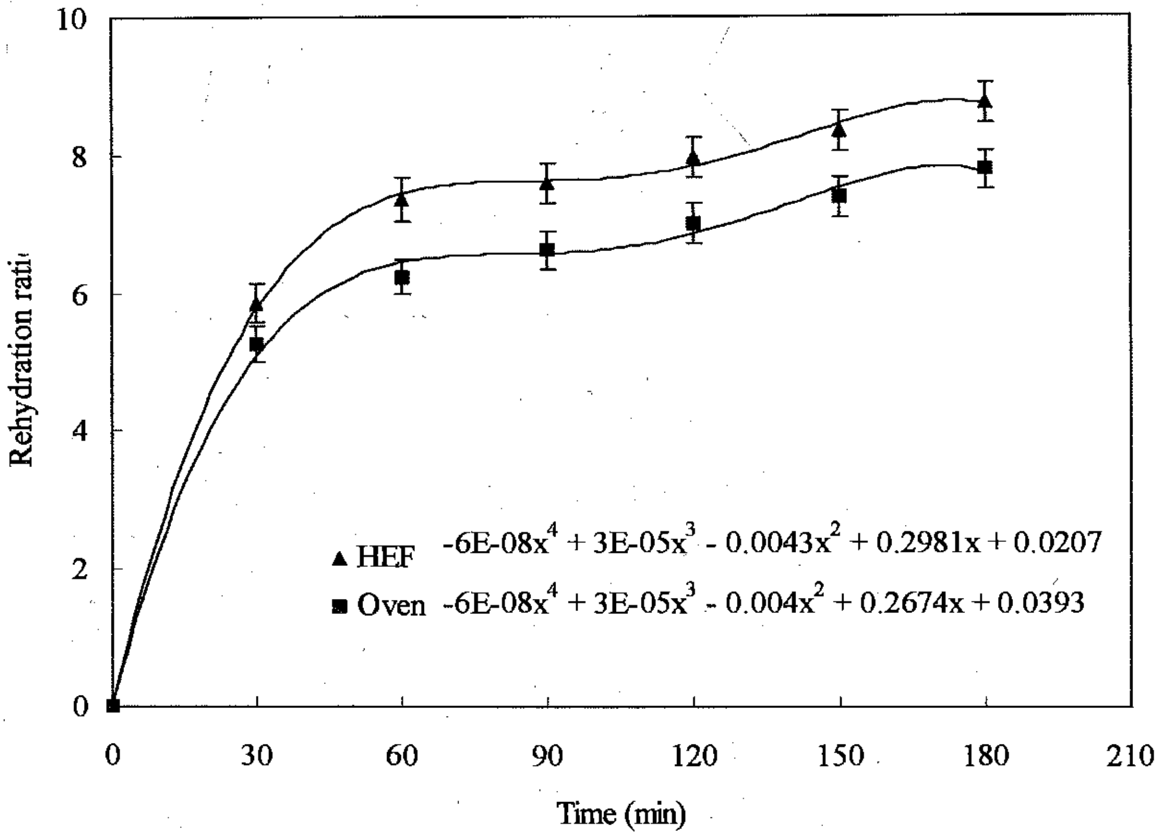


Figure 5: *Rehydration ratio for HEF- and oven-dried radish slices at 25°C*

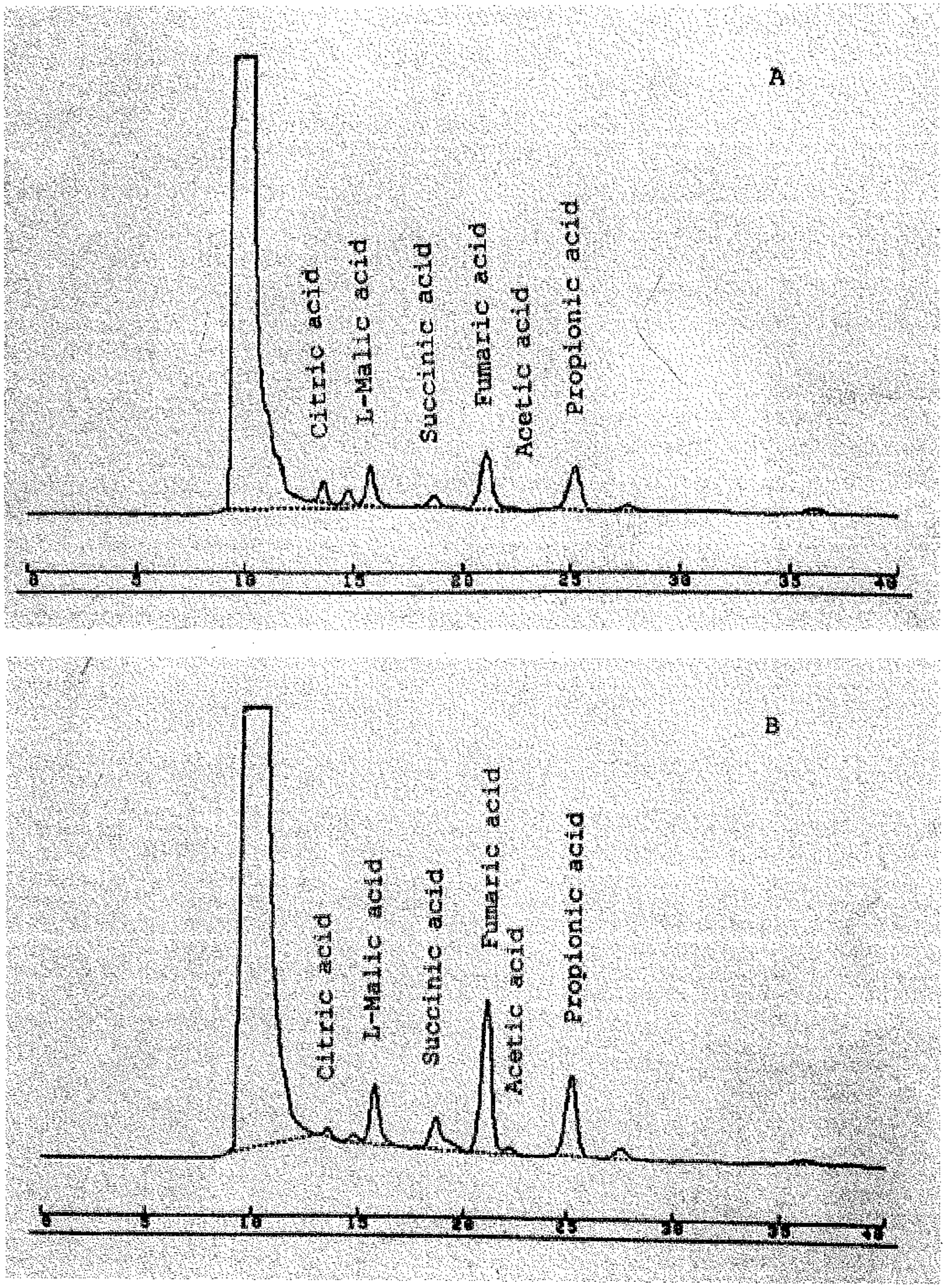


Figure 6: *HPLC profiles for organic acids of HEF and oven dried spinach samples with peak area (Bajgai & Hashinaga, 2001b)*

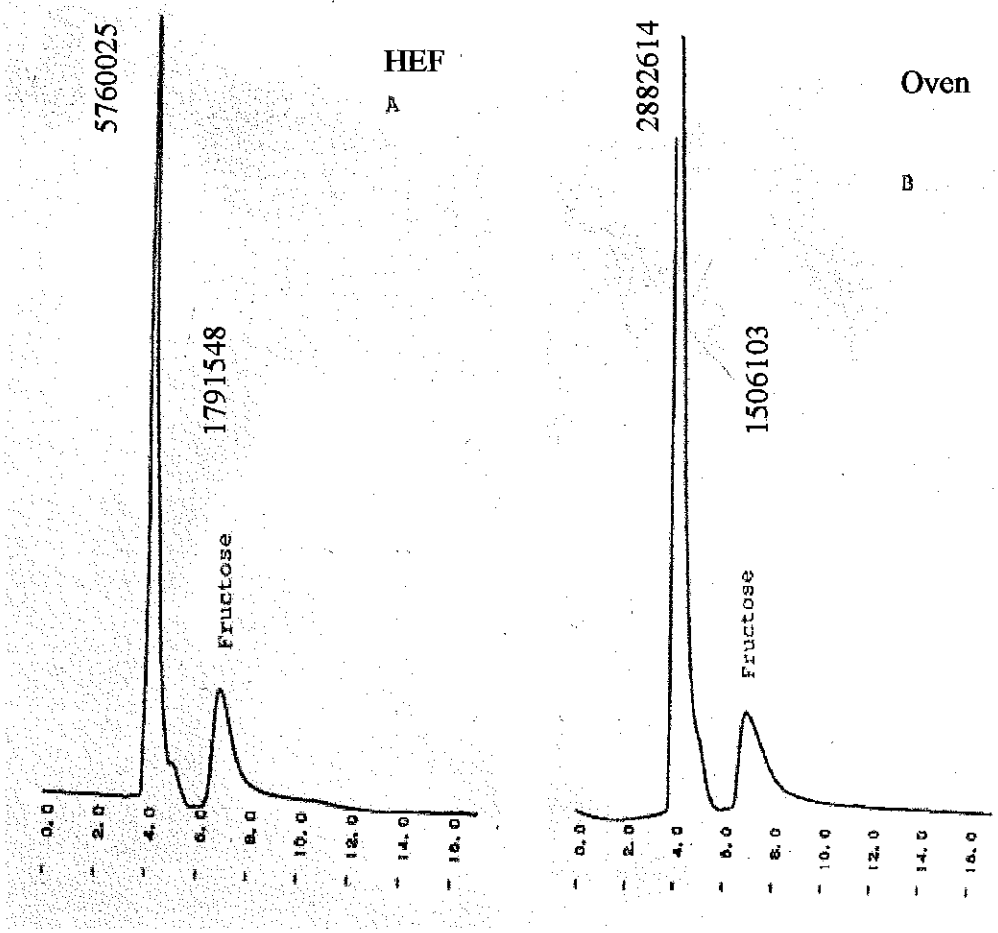


Figure 7: *HPLC profiles for sugar of HEF- and oven- dried spinach samples with peak area (Bajgai & Hashinaga, 2001b).*

Table 2: *Voltage and ionic current during air ion application in drying*

Authors	Voltages (V)	Current (I)
Lai and Wong, 2003	55.1-102.4 kV/m	6-11 µA
Bajgai and Hashinaga, 2001a	430 kV/m	-
Bajgai and Hashinaga, 2001b	430 kV/m	-
Hashinaga et al., 1999	430 kV/m	0.6µA
Isobe et al., 1995	667 kV/m	12.6µA
Hashinaga et al., 1995	680 – 1280 kV/m	-
Cheng and Barthakur, 1995	525 kV/m	50µA
Cheng and Barthakur, 1994	525 kV/m	3 mA
Carlong and Latham, 1992	700 kV/m	-

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