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COMMUNICATION

A New High-Yield Process for the Industrial Production of Carrot Juice

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Abstract A new carrot juice production process has been developed to improve the yield of product to values higher than 80%. This result was obtained by properly processing, with consolidated technologies, both the liquid and the solid streams coming from the decanter of a traditional carrot juice industrial plant. In particular, the above-mentioned solid stream (waste of the decanter) was further processed by using an aqueous washing stream consisting of the endogenous vegetation water contained in the processed carrots. This stream can be obtained, in the required amount, in a reverse osmosis section which is fed with the liquid stream coming from the decanter of a traditional carrot juice production plant. A special feature of the proposed process is that it uses an endogenous washing vegetation water stream, thus avoiding any kind of contamination of the final product. A detailed description of the washing and the reverse osmosis section, the values of the corresponding operating parameters, and validation of the results obtained by calculation were reported and discussed.

Keywords Carrot juice · Reverse osmosis · Yield improvement

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Introduction

Carrot juice is produced from carrots (*Daucus carota*), a vegetable root widely cultivated in many parts of the world. Like most other vegetables and fruit, carrots are essentially made up of vegetable water (VW), more than 90%, besides other soluble solids (sugars, proteins, B and C vitamins, and minerals), insoluble solids—mainly dietary fibers, water insoluble β-carotene (Provitamin A), and a very small amount of fat; its characteristics and bright orange color are related to the content of β-carotene properly protected by inactivation of oxidative enzymes (Quitão-Teixeira et al. 2008). Consequently, carrot juice has a high nutritional value and it is often marketed as a health drink. Using traditional methods, a kilogram of properly pre-treated carrots will yield from 0.5 to 0.55 kilograms of juice depending on the production process as well as on the carrot variety. With enzymatic maceration pretreatment (Sun et al. 2006; Liao et al. 2007; Demir et al. 2004, 2007; Kaur et al. 2009) the yield can be improved by up to 0.65. However, this pretreatment is considered a kind of contamination. This is, however, still not a high yield if compared to that of apples and oranges; the main difficulty in juicing carrots being related to the solid–liquid separation. Cassano et al. (2003) showed that reverse osmosis (RO) can be conveniently used to concentrate the carrot juice. The purpose of the present study was to demonstrate that a significantly higher yield can be achieved by adding to a traditional carrot juice production process, a proper RO section coupled with a proper washing section in order to recover most of the total soluble solid content (TSS) of the carrot. In fact, in this way, it is possible to significantly improve the yield of juice while avoiding any kind of contamination of either the liquid product or the insoluble fiber-rich fraction (IFRF) valuable by-product.

Materials and Methods

Materials

All the carrots, the carrot juice and the wetted solid phase separated in the decanter (WOD), were obtained directly from a traditional industrial plant located in the agro-industrial district of Fucino, close to the laboratory and other research facilities used by the authors of the present paper. Both the above-mentioned solid-like materials were characterized with respect to dry weight, concentration of TSS, sugar, insoluble fibers, and carotenes; the juice was characterized for sugar and carotene content. One hundred grams of the edible part of carrots or, alternatively, of WOD, were ground and dried in a small oven at 340 K, under N_2 atmosphere, until the weight of the dried material reached a constant value. The dried solid was then cooled, stored in a small glass container, previously evacuated, and weighed on an analytical scale (Mettler, $\pm 10^{-4}$ g).

The concentration of TSS and of insoluble fibers was obtained by completely dissolving the water soluble part of dried material. To this purpose, about 10 g of previously weighed dried solid was washed ten times by using about 50 ml of purified water at 310 K each time. Then the wetted insoluble solid phase was dried, using the same procedure already described, and weighed.

Both sugar and total carotenes, as β-carotene, were analyzed with HPLC using a chromatographic system composed of a Model 515 pump (Waters, Milford, MA, USA) equipped with a Model LS 30 Fluorescence Spectrometer (Perkin-Elmer) as detector for carotenes, and a Model Varian Star 9040 Refractive Index as detector for sugars.

Pure compounds used for preparing calibration curves, were purchased from Fluka (Buchs, Switzerland); organic solvents were purchased from Sigma-Aldrich (Milan, Italy), and water (HPLC-grade) was obtained with an Elix 3 Water System and passed through a Milli-Q Academic water-purification system (Millipore, Bedford, MA, USA).

The method used to find the concentration of sugars is based on treatment with an aqueous (40%) solution of lead acetate in order to obtain deproteinization and decoloration of the samples which, before entering into the HPLC system, are properly filtered. A preliminary homogenization treatment is required when starting with solid material.

The method used to find the concentration of carotenes is based on saponification, in order to separate the hydrophobic part which contains the carotenes. To this purpose, the material to be analyzed was treated with ethanol, ascorbic acid, Na_2S, KOH and purified water in the ratio of 80/1/0.04/12/20. After reaction and solid–liquid separation the carotenes were recovered with hexane.

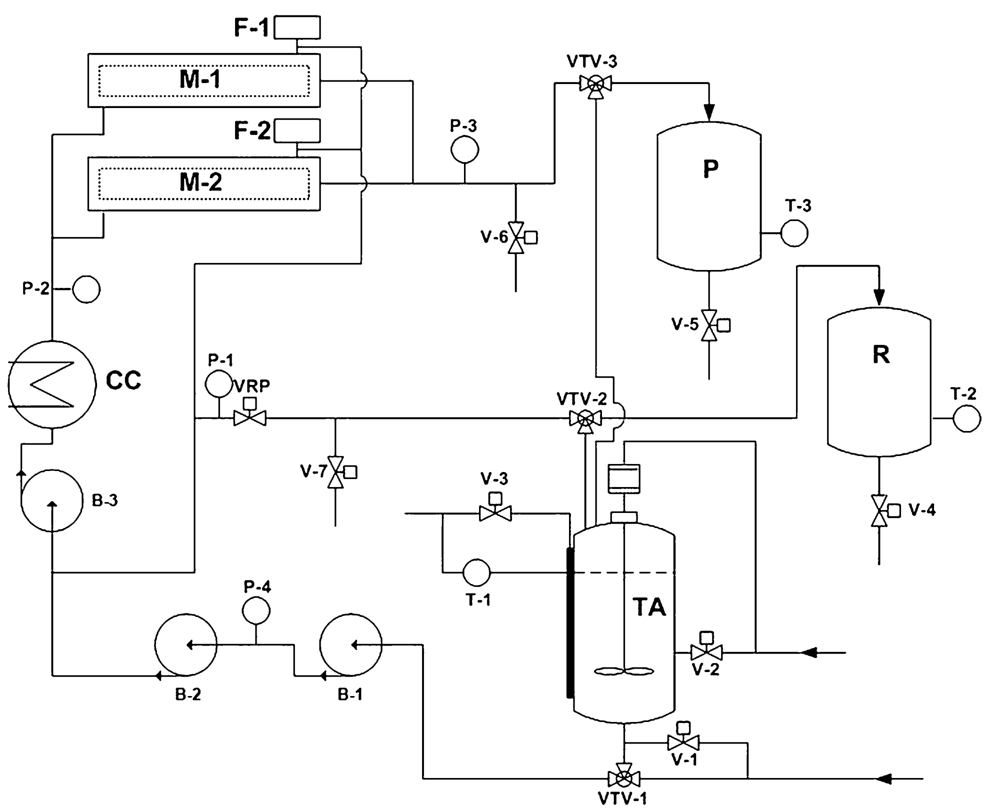

Fig. 1 Schematic flow diagram of the RO pilot plant. *TA* feed tank, *P* permeate reservoir, *R* retentate reservoir, *M-1,2* membrane modules, *B-1,3* pumps, *VRP* pressure regulation valve, *VTV-1,3* flow regulation valves, *V-1,7* on–off valves, *P-1,4* manometers, *T-1,3* thermocouples, *CC* heat exchanger, *F-1,2* flow meters

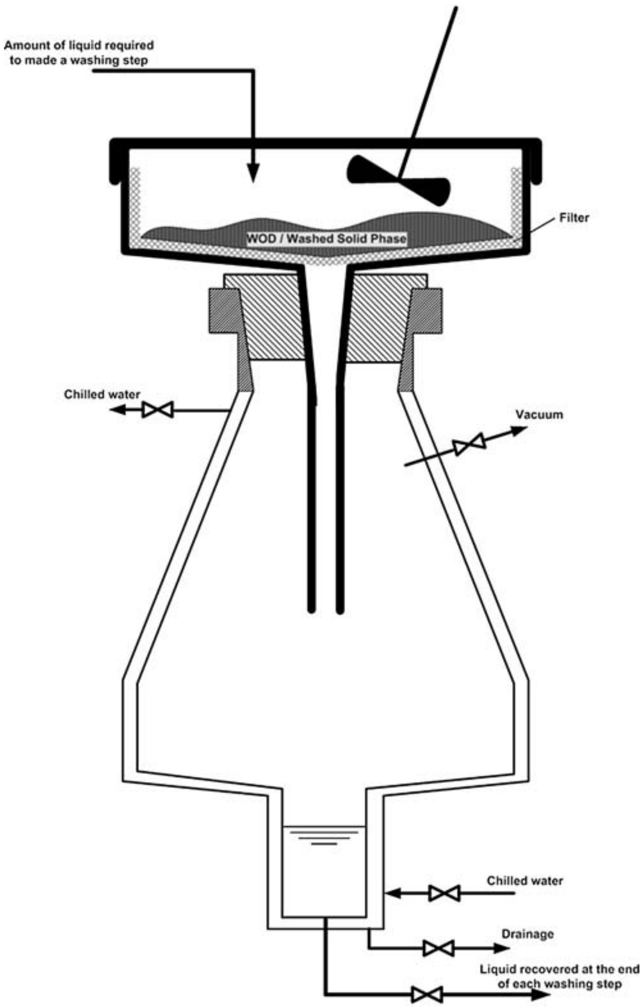

Fig. 2 Laboratory apparatus used to perform the washing experimental tests

Experimental

The first part of the experimental work was finalized to verify the feasibility of using a RO section to obtain a sufficient amount of permeate with the quality required to be used in the washing section. To this purpose, the RO pilot plant (Niro-Soavi) shown in Fig. 1 was used, operated in continuous mode and equipped with two composite polyamide spiral wound modules (GEA-TFC 3838) having an external diameter of about 0.1 m and a length of about 1 m.

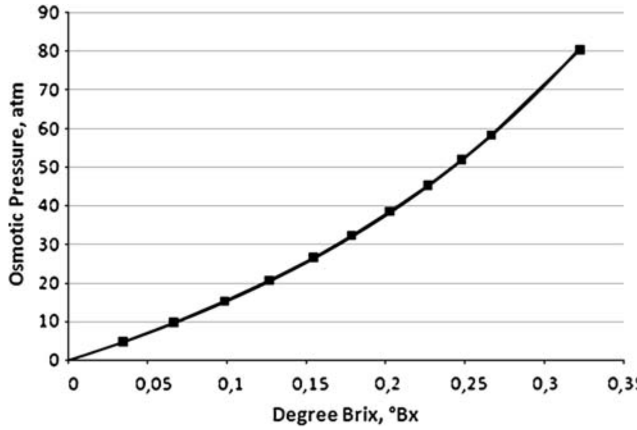

Fig. 3 Osmotic pressure of aqueous solutions of fructose as function of solute concentration. Absolute Average Deviation (AAD)=0.75%

The second part of the experimental work was finalized to quantify the properties of both solid and liquid phases obtained by washing the WOD several times, on a laboratory scale, always using a portion of the permeate, VW, produced by the RO pilot plant.

The washing experimental tests were made using the laboratory apparatus shown in the Fig. 2. A weighed amount of WOD, typically 225 g, was fed into the funnel covering the glass vessel (1.5 l). Before feeding the WOD in, the sides of the funnel were covered with a filter. Then the funnel was closed, the vessel below was evacuated, and 46 g of VW obtained by the RO plant, shown in Fig. 1, were added, and the filtered liquid was recovered. This step was repeated four times, thus simulating a continuous crosscurrent multistage washing section.

Results and Discussion

The results of the characterization of carrots along with the corresponding WOD and juice obtained from the traditional

Table 1 Average composition of the edible part of different carrot lots and related solid and liquid products, produced by a traditional plant

	Carrots	WOD	Juice
Dry weight (%)	13.5±0.5	20.1±1.0	–
TSS (%)	7.2±0.5	6.9±0.5	–
Sugar (%)	6.6±0.4	6.1±0.4	7.0±0.4
Insoluble Fibers (%)	4.0±1.0	8.9±1.0	–
Carotenes as β-carotene (ppm)	100±6	111±6	91±6

Table 2 Results of the laboratory scale washing experimental tests

	WOD	1st WS	2nd WS	3th WS	4th WS	Total reduction
TSS (g)	15.5	12.3	9.8	7.8	6.2	60%
Carotenes as β-carotene (ppm)	111	109	107	106	106	4.5%

AAD_{TSS}=4%; $AAD_{carotenes}$=3%

WS washing stage

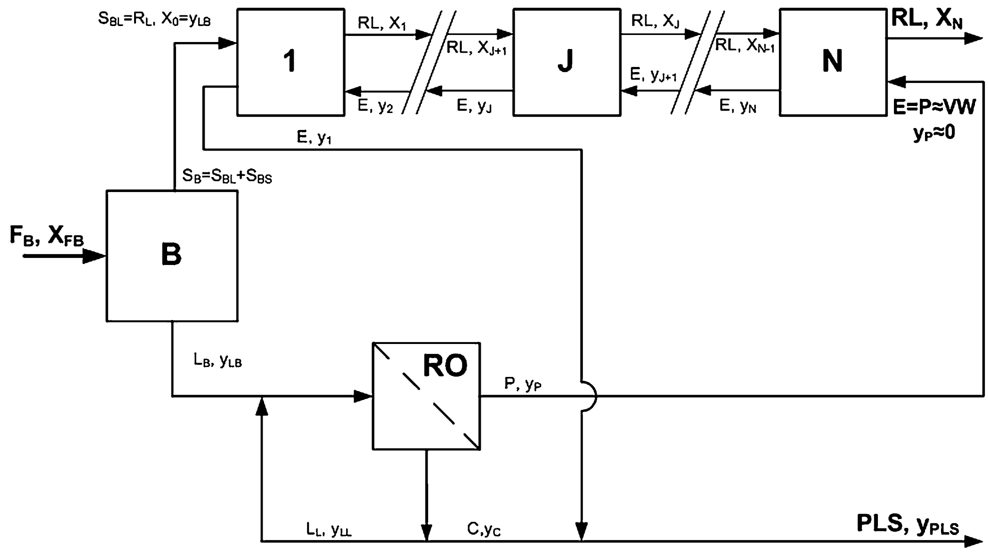

Fig. 4 Schematic flow diagram of the high-yield carrot juice production process

industrial plant mentioned in the previous section are reported in Table 1. All the values reported in the table represent the average of several analyses made from the materials obtained from different carrot lots.

As a result of the experimental tests made using the RO pilot plant it was found that it is feasible to produce a permeate stream which, both for rate and quality, can be used for washing the WOD, while operating with values of pressure, temperature and recirculation ratio of the retentate stream (RRR) typical of industrial RO plants. In fact, it was found that, at 50÷55 bar, ambient temperature and RRR equal to 5, the amount of permeate is more than 2/3 of the feed stream with a TSS and β-carotene concentration lower than 0.1% and 0.1 ppm, respectively. This value of the operating pressure is compatible with the previous experience of the authors in concentrating a variety of natural aqueous solutions of sugar and with the osmotic pressure of aqueous solutions of fructose (Fig. 3) calculated by using the activity coefficients of the solute reported by Gaida et al. (2006), to account for the non-ideality of the solution. In particular, the line reported in Fig. 3 was calculated by using the physical–chemical model for the activity coefficients of fructose, while the osmotic pressure corresponding to each black square was calculated by using the pseudo-experimental value of the activity coefficient of the solute obtained by Gaida et al. (2006), after numerical transformation, with the Gibbs–Duhem equation, of water activity data.

With reference to the operating pressure and to the retentate concentration of the RO section it is important to point out that the activity coefficient of fructose is quite a bit higher, in the whole range of the considered concentration, than the same corresponding property in other sugars.

The results of the laboratory scale washing experimental tests are reported in Table 2.

As shown, most of the TSS can be removed during the solid phase while the washing process does not significantly change the concentration of β-carotene in the washed solid phase. It is worth pointing out that, when using the same amount of washing liquid in a countercurrent apparatus, instead of the crosscurrent one simulated in the laboratory experimental tests, the removal of TSS can be improved significantly, while it is reasonable to expect that the removal of carotenes be unaffected. In fact, the TSS is dissolved in the washing stream while the insoluble

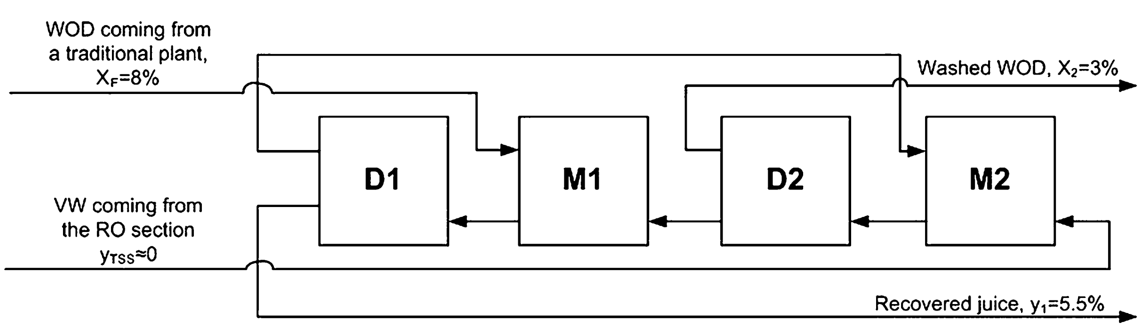

Fig. 5 Schematic flow diagram of a two-stage countercurrent washing section equipped with two decanters (*D1* and *D2*) and two mixers (*M1* and *M2*)

carotenes are only removed by mechanical action (dragging). Since in the production of carrot juice the yield is defined as the ratio of the TSS recovered in the juice to the total amount of TSS contained in the whole carrots, all the above-mentioned experimental results show that the yield can be improved while avoiding any kind of contamination, potentially related to the addition of extraneous substances, like enzymes or exogenous water. In addition, the solid washed phase remains a valuable by-product which can be used as an ingredient in the production of fiber-rich dietary food, or as raw material, as an alternative to whole carrots, for producing carrot oil (Castellani et al. 1996). The schematic diagram of the enhanced carrot juice industrial process is shown in Fig. 4, where: F_B (kg/h), X_{FB} (kg/kg) represent the feed of the up-streamed carrots into the traditional plant (B), and the corresponding weight fraction on insoluble solid free basis of TSS, respectively; L_B (kg/h), y_{LB} (kg/kg) represent the carrot juice coming out of the traditional plant, and the corresponding weight fraction of TSS, respectively; S_B (kg/h) represents the waste of the decanter made of the insoluble solids fraction (S_{BS}), and of the liquid fraction of the wetting solution (S_{BL}); R_L (kg/h), X_j (kg/kg) represent the constant fraction of the liquid solution wetting the solid stream coming out from each ideal stage of the washing section, and the corresponding weight fraction on insoluble solid free basis of TSS, respectively; E (kg/h), y_j (kg/kg) represent the constant liquid washing stream coming out of each ideal stage, and the corresponding weight fraction of TSS, respectively; 1, j, N represent the first, the jth, and the last ideal stage of the washing section, respectively; P (kg/h), y_P (kg/kg) represent the permeate stream coming out of the RO section, and the corresponding weight fraction of TSS, respectively; C (kg/h), y_C (kg/kg) represent the product fraction of the retentate stream coming out of the RO section, and the corresponding weight fraction of TSS, respectively; L_L (kg/h), y_{LL} (kg/kg) represent the re-circulated fraction of retentate coming out of the RO section, and the corresponding weight fraction of TSS, respectively; PLS (kg/h), y_{PLS} (kg/kg) represent the total amount of the carrot juice coming out of the enhanced process, and the corresponding weight fraction of TSS, respectively.

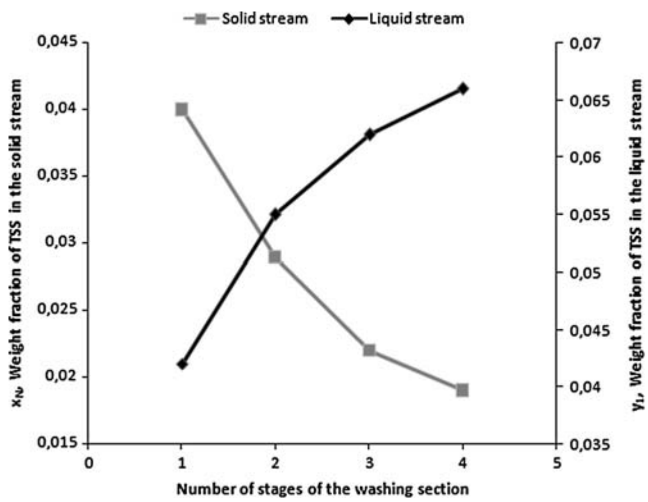

Fig. 6 Behavior of the calculated weight fractions of both the liquid (y_1) and the solid (x_N) streams coming out of the washing section, as function of the number of the ideal stages

As can be seen, this was obtained by properly adding to a traditional carrot juice production process (B), an RO section equipped with a plant similar to the one shown in Fig. 1, and a multistage countercurrent washing section which is actually made by a number (j) of properly arranged ideal mixer-settlers as shown in Fig. 5.

The material balance around B and around RO were reported on Table 3. The calculations were made with reference to 1.0 t/h of up-streamed carrots fed to B; it was also assumed that B operates with a yield of 55%, producing a carrot juice liquid stream at 8% of TSS in addition to a solid WOD by-product which is composed of 86.8% of wetting liquid, having the same composition as the product, and of 13.2% of insoluble solid material. All the above-mentioned assumptions are compatible with the experimental characterization of raw material, intermediate, and product streams, as well as with the RO pilot plant experiments.

Using these results, it was possible to predict the performance of the ideal multistage countercurrent washing section by assuming that: (a) $X_j=y_j$; (b) the mass flow rate of the whole-wetted raffinate stream (R) is constant for each stage and equal to that of the feed (S_B); c) the mass flow rate of the wetting liquid fraction of the raffinate (RL) and

Table 3 Results of the material balance made around B and around RO, with reference to Fig. 3

	F_B	S_B	L_B	S_{BS}	S_{BL}	P	C	L_L
kg/h	1,000	454	546	60	394	364	182	907
X	00:08	00:08	–	0	–	–	–	–
y	–	–	00:08	–	00:08	0	00:24	00:24

X weight fraction of TSS on solid free basis in the solid streams, y weight fraction of TSS in the liquid streams

Table 4 Performance of a carrot juice production process as function of the number of stages of the washing section

	0	1	2	3	4
y_{PLS}	0.080	0.110	0.117	0.121	0.124
x_N	0.074	0.040	0.029	0.022	0.019
Yield	0.55	0.80	0.85	0.88	0.90

x_N represents the weight fraction of TSS in the whole-wetted solid by-product.

of the extraction (E) streams are also constant; (d) consequently, E is equal to the mass flow rate of the permeate (P) coming out from the RO section. Under these conditions, X_j and y_j can be calculated by solving the following tridiagonal system, representing the material balance of TSS made around each stage.

$$\begin{aligned} &\mathrm{RL} \times X_0 + E \times y_2 = (\mathrm{RL} + E) \times y_1 \\ &\mathrm{RL} \times X_{j-1} + E \times y_{j+1} = (\mathrm{RL} + E) \times y_j \\ &\mathrm{RL} \times X_{N-1} + E \times y_p = (\mathrm{RL} + E) \times y_N \end{aligned} \quad (1)$$

Considering that both the first and the last equations are characterized by only two unknowns, instead of three, this system can be solved starting from the bottom equation to obtain, in particular, the TSS concentration of the E stream coming out of stage 1 (y_1), as well as the TSS concentration of the RL stream coming out of stage N (X_N). The behavior of the calculated weight fractions of both the liquid and the solid streams coming out of the washing section is shown in Fig. 6, as a function of the number of ideal stages.

The amount of TSS recovered in the washing section is added to the retentate stream (C) coming out of the RO section, thus improving the total amount of TSS in the Product Liquid Stream (PLS).

As an example, the results obtained by considering a two-ideal-stage washing section (Fig. 4) are reported in Table 4, along with the results related to processes equipped with washing sections having a different number of ideal stages. In the same table, the performance of a traditional carrot juice production process (number of washing stages equal to zero) was also reported for comparison.

As can be seen, the enhanced process shown in Fig. 4 is characterized by a yield improvement which is always higher than 45%; this value corresponds to a washing section with only one stage. In addition, as already pointed out, the sugar concentration in the solid by-product becomes significantly low.

Conclusions

The present study demonstrated that carrot juice can be produced with a yield higher than 80% without using any extraneous substances, like enzymes or exogenous water, as a guarantee against any kind of contamination and/or variation of typical organoleptic properties. In addition, it was found that the β-carotene concentration in the waste of the decanter is not significantly affected by the proposed treatment, while the concentration of sugar is drastically reduced. Consequently, the solid by-product has better properties for it to be used as an ingredient in preparing functional food or as a substitute of whole carrots for extracting carrot oil. The enhanced process developed in the present study makes use of only consolidated technologies, properly connected.

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