Industry 4.0 Technological Elements Applied to Steam Distillation

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The essential oil extraction industry is a stimulating target for technology updates in which yield, quality, and energy efficiency are goals to be pursued. This step forward becomes a strong ally in the search for continuous improvement of these key indicators. This work proposes the implementation of Industry 4.0 elements to detect and correct the preferential steam paths (channeling), determine the economic duration of the process, and reduce volatile element losses with efficient condensation. Partial experimental results indicate yield gains more significant than 20% and improvement in product quality indicated by the greater presence of the Citral component in the chromatographic analyses. Furthermore, the experimental results, still ongoing, demonstrate that the design of a plant with sensors, actuators, and process monitoring systems is auspicious.
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Introduction

Essential oils are natural products extracted from plants (flowers, barks, stems, leaves, roots, fruits, and seeds) with essential applications in industry. Chemically, they are composed of a range of fractions, from the terpenoid family, in a homogeneous mixture, from the most volatile to the heaviest. As a result, they have a pronounced aroma, often pleasing to the human sense of smell. With rare exceptions, their density is lower than water, with a characteristic color for each species varying in intensity [1,2].

Among the various extraction methods, steam distillation is responsible for more than 90% of the worldwide produced volume [3-5].

The steam distillation consists of flowing steam upwards through the aromatic plant (raw material) inside an extraction vessel. Steam has two roles: supply heat to break the cells in which the essential oil is stored (in the plant cells) and carry it until the condenser. The condenser is a shell-tube heat exchanger that liquefies the mixture of steam-essential oil. A separate vessel receives that fluid to isolate the essential oil and the condensed hydrosol. Hydrosol is a stable emulsion of essential oil into the water, hard to break, and has poor economic feasibility. Nevertheless, it is also a market-interest product [1,2,5]. Figure 1 is a sketch of a typical installation with a heat source, extraction vessel, condenser, and vessel for collection and separation (essential oil-hydrosol)

The technological scenario in the EO (Essential Oil) extraction industry via steam distillation brings attractive updating opportunities for yield, quality, energy efficiency, and operational effectiveness continuous improvements [6]. Side by side with technological evolution, environmental performance is increasingly receiving attention. The so-called green extraction brings perspectives and systematization to the initiatives related to sustainable process design [7,8].

For terminology purposes, in this paper, the yield is calculated from the relationship between the extracted essential oil volume (mL) and the raw material mass of fresh raw material (kg). Quality means adherence to specifications and is usually verified via GC – gas chromatography in this industry.

Industry 4.0 is a term used to designate the 4th industrial revolution. It emphasizes the integration of machines with the capability to exchange information and adapt autonomously to market expectations, using its enabling technologies

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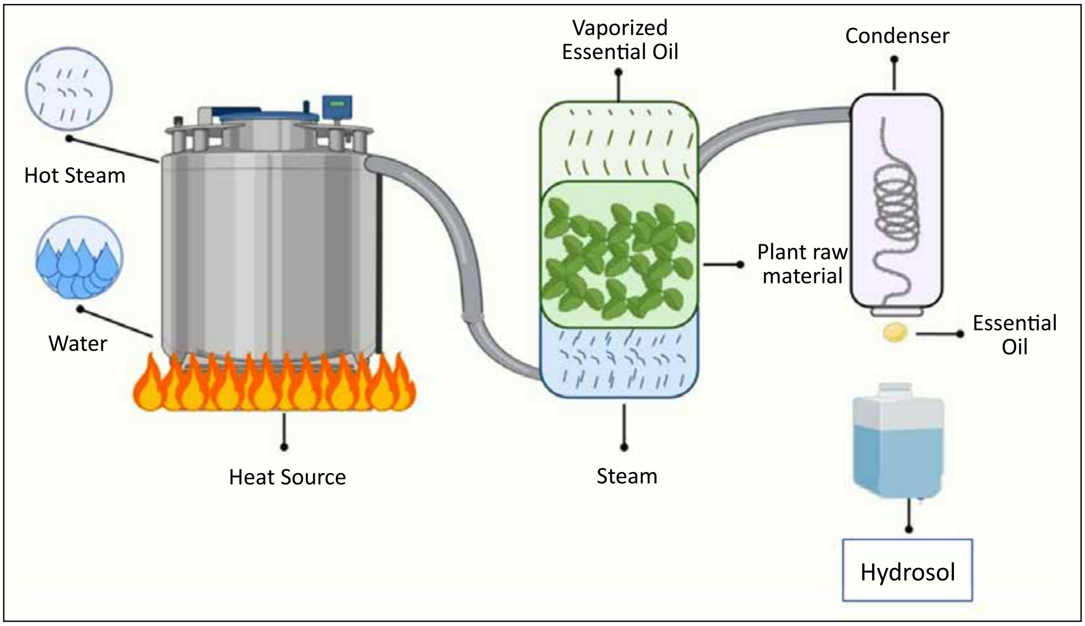
Figure 1. Conventional essential oil steam distillation installation.



and responding smartly to variable and complex demands [9, 10].

Manufacturing is one of the crucial operations within a Supply Chain Organization. Its objective is to meet or exceed performance expectations related to customer service at the right time, quantity, and quality. The technologies brought by wave 4.0 are intended to build capabilities to fulfill business growth and perennity strategies, given the current environment of uncertainties and difficult business predictability [11-13].

Technology update for the essential oil industry embeds innovative instrumentation design for production systems, automatic controls, and process monitoring. The intense dependence on the workforce requires continuous action from the operators to control essential process parameters [14].

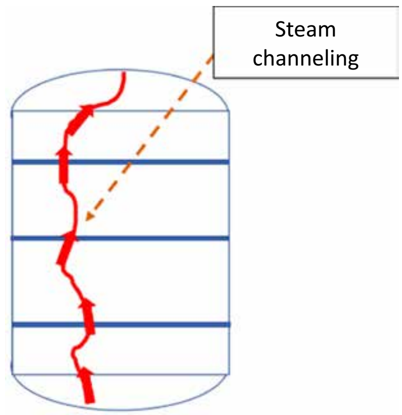
The generation of a process database, its formatting, and analysis enable the investigation to determine good variable correlations and, consequently, create a model. When this model dynamically adapts and proposes improved parameters to the actual process, it is called a digital twin [15]. Moreover, it is a near-real-time digital image of a physical process [10] or, in other words, the cybernetic and physical spaces joining in the manufacturing environment towards optimization [16].

The proposed concept of an intelligent essential oil plant, considered in this work, aims at demonstrating potential benefits arising when proper technology elements are applied, detecting and correcting critical process deviations. These deviations are well-known in the industry, without adequate processes to deal with them. Therefore, this article focuses on three crucial process weaknesses.

The first, channeling, consists of steam paths through the raw material [17] with preferential trajectories (Figure 2). It happens mainly due to the natural anisotropy of the plant medium inside the extractor. This occurrence causes poor yield where the steam flow is less intense and promotes degradation where the aromatic plant is overexposed to heat [1,5,18]. Therefore, channel detection and correction positively impact yield and quality [19].

The second is the determination of the economic extraction duration. This critical process parameter

Figure 2. Steam channeling representation.



also influences both yield and quality. If longer than necessary, light fractions of the extracted essential oil are lost to the atmosphere and overexpose the raw material to high temperatures. If shorter than necessary, extraction is incomplete, affecting yield results [18, 19]. Figure 3 demonstrates how extraction time can impact process results. Instant t1 indicates the maximum slope of the yield curve.

The interval between t1 and t2 presents asymptotic behavior when the yield rate decreases, and the continuity of extraction depends on economic viability; that is, the extracted volume compensates for or exceeds the general production costs. On the other hand, the interval between t2 and t3 represents the time without any economic benefits. In fact, during this period, yield can even decrease once the light fractions can be lost and degradation can take place.

The third is the use of condensation water at a controlled temperature. Usually, extraction industries apply water at room temperature. When chilled water is used, condensation is more efficient, and losses due to evaporation are minimized.

The above-highlighted points are a kickoff for this research field; deepening and exploring such technological subjects to promote a step forward, mainly for small and medium-sized producers who access technology, may become more difficult [5].

There are countless possibilities for digital technology implementation, depending on the operational needs and resources available for investments. However, what is unquestionable is the need for technological upgrading of this industrial branch. Figure 4 shows how precarious some extraction units are.

Thus, the objective of this work consists of a proposal for intelligent digital technologies to improve the extractive processes of essential oils by steam distillation.

Materials and Methods

Figure 5 displays the installation configurations before and after introducing the proposed technological elements, which will be detailed in the text.

Channeling detection and correction, automatic (economic) process duration determination, and condensation water with controlled temperature were the focus of the experiments.

For channeling detection, six thermocouples were installed directly in the raw material, without the thermowell, to obtain quick signal transmission, according to Figure 6.

The module of temperature differences for each pair of thermocouples (TT1 and TT2; TT3 and TT4; TT5 and TT6), when above an adjusted setpoint (to be determined experimentally), indicates that the steam is flowing preferentially through a path (the channeling). When detected, a correction occurs with the stepper motor, with small pulses to re-accommodate the aromatic herb inside the extractor vessel, continuously seeking to suppress the channeling.

For the economic process duration determination, an image processing system was applied. The essential oil–hydrosol mixture is collected and separated in a transparent vessel. So, the camera detects the level it becomes stable, and the extraction continuity would not be economically justified.

Water for condensation was designed to be supplied with a controlled temperature from a chiller.

Figure 3. Yield (Y) vs. extraction duration (t).

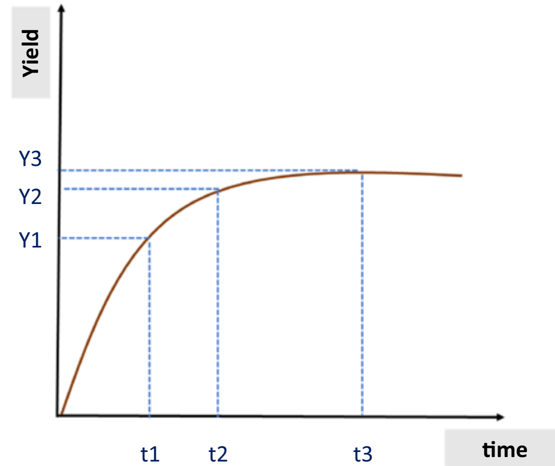


Figure 4. Typical steam distillation installation.

Figure 5. Installation before and after proposed interventions.

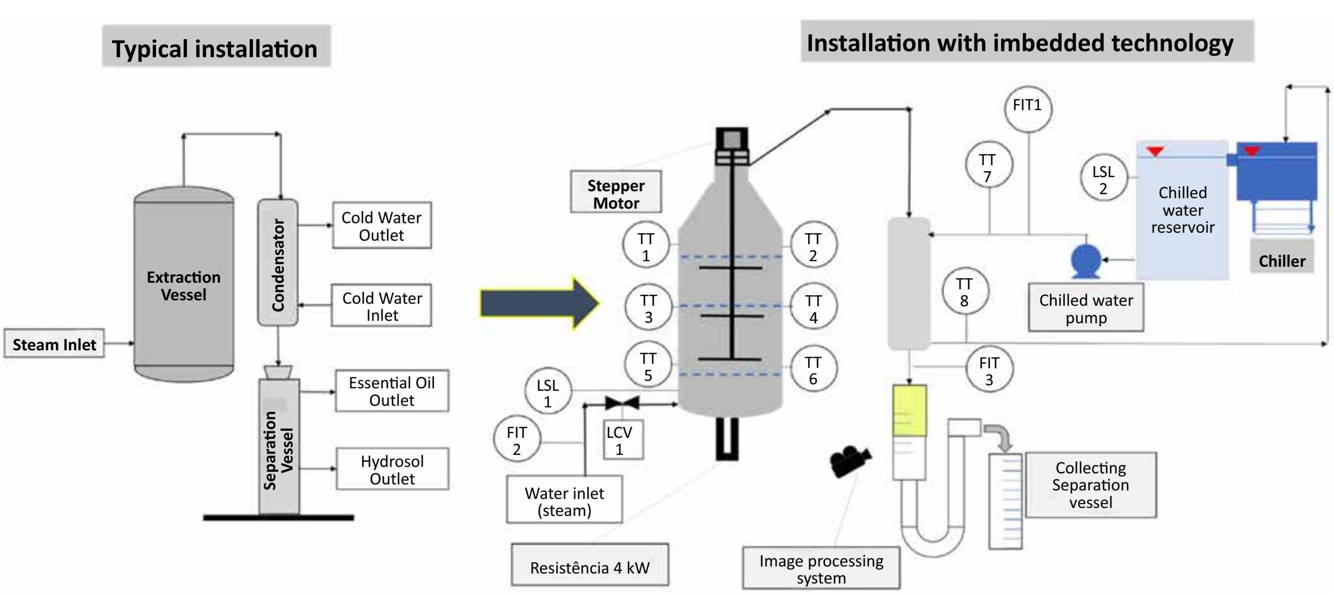
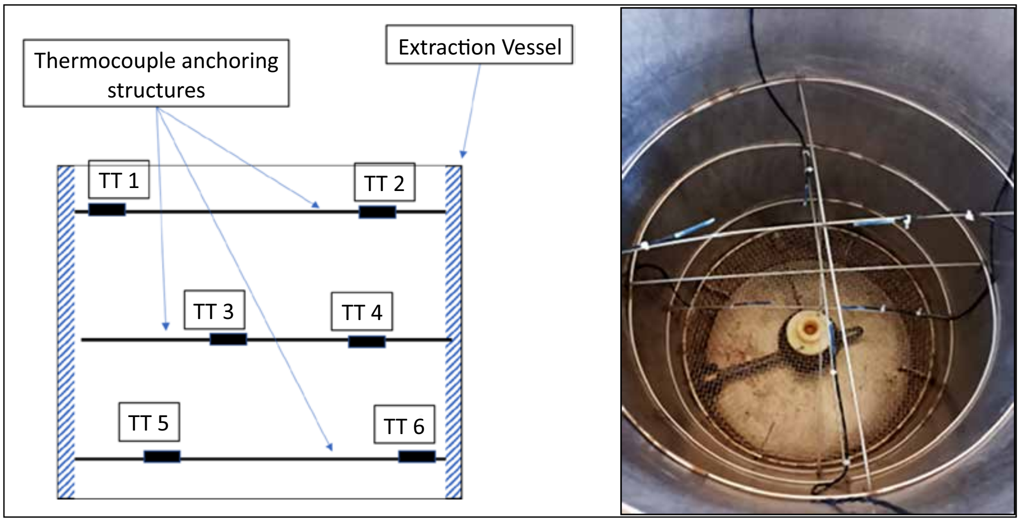


Figure 6. Channeling detection - Thermocouple installation detail.



All these systems were controlled by two PLCs (Programmable Logic Controller) and a SCADA (Supervisory, control, and data acquisition system), and MMI (Man-machine interface).

As a raw material for the experimental phase, lemongrass (*Cymbopogon citratus*) was selected due to the availability of prompt supply. Preparation consisted of drying in the shade for 48 hours and chopping for approximately 20 mm particle size. The essential oil of lemongrass presents Citral as the main component of interest. Therefore, Citral content will be considered a quality indicator. Analysis was performed using chromatography.

Results and Discussion

Partial experimental results indicated progress in process indicators when technological elements are added.

Channeling was detected as expected (Figure 7). The plot of process temperatures TT1 to TT6 indicated differences in channeling evidence. Each pair of thermocouples, at the same level, should indicate approximately the same temperature (TT1 and TT2; TT3 and TT4; TT5 and TT6).

Channeling correction occurs when temperature differences (module) exceed 5 C. The stepper motor was driven to move at a slight angle of 3 to 5 degrees and accommodate the raw material.

The image processing system detected the progress and determined the economic duration of extraction. The decision to conclude the extraction comes from comparing the value of the essential oil extracted in the last period with its operational cost. The processing time, usually 2 hours in the industry, could be reduced to 40 – 50 minutes, meaning a significant capacity increase and energy consumption reduction. Figure 8 illustrates one of the experiments.

Preliminary yield results were 3,7 mL/kg and 4,6 mL/kg, without and with embedded technology), respectively. A sequence of experiments will be performed to confirm that positive trend. Quality-wise, the content of Citral increased from 69% to 76%, detected by gas chromatography, so far confirming that condensation water with controlled temperature is adequate.

Conclusion

The ongoing experimental phase indicates that the objective of exploring technological updates for essential oil extraction via steam distillation can bring yield and quality enhancement, as well as reduce process duration and energy consumption. The continuity of the experiments should confirm this positive trend obtained so far.

Figure 7. Channeling: temperature profile.

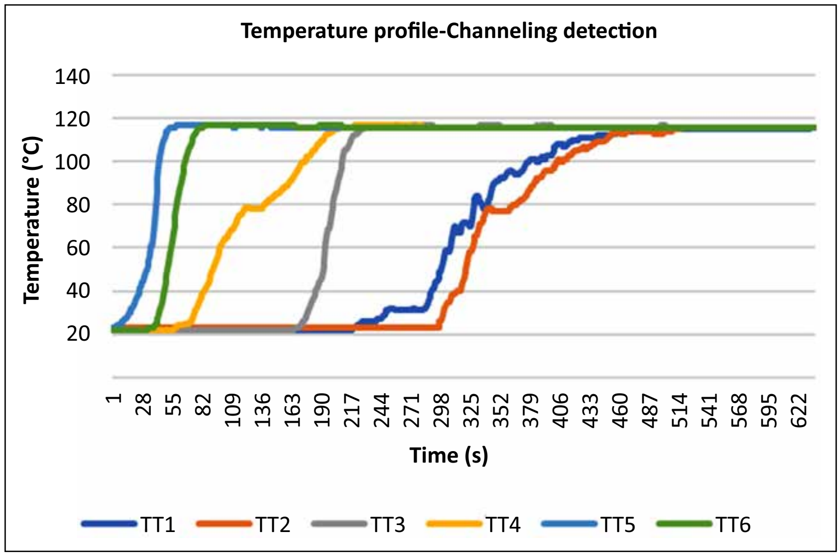
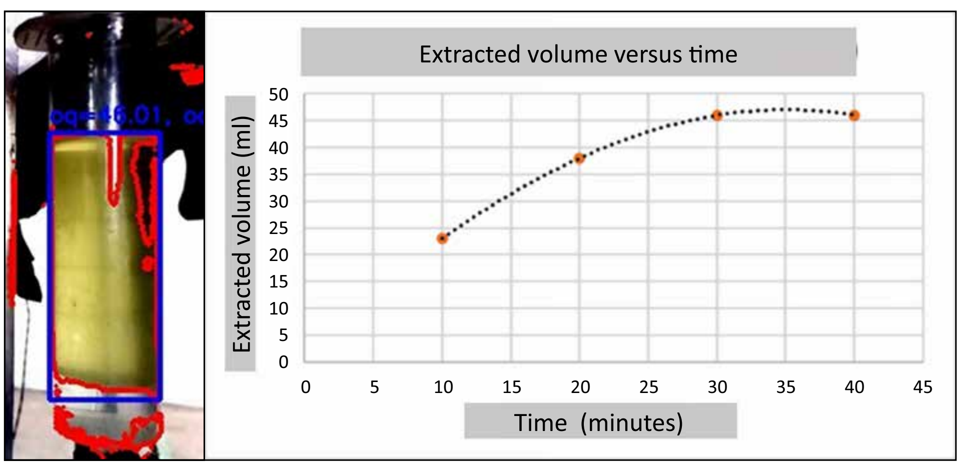


Figure 8. Image processing system determining the extraction endpoint.



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