Testing of ultrasonic vibration to speed up the remuage operation in sparkling wine production

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Abstract

In order to expedite the remuage process, the research tests the application of ultrasonic vibrations directly induced into the bottles with the goal of offering a novel method. This ultrasonic method creates vibrations that speed up the lees' movement down the slanted bottle's slope, accelerating their accumulation in the bottleneck. Additionally, image analysis was used to gauge the method's effectiveness, and sensory analysis was used to assess how the procedure affected the wine. The tested system was put into practice, and it saved a lot of time (2.5 hours) during the *remuage* process without affecting the wine's sensory qualities (no statistically significant differences were found at 99.9% when compared to traditional *remuage* methods). Moreover, the manuscript addressed the advantages and disadvantages, both external and internal, that the research outputs face during the possible implementation of the prototype for ultrasonic for ultrasonic remuage. One can envision a future replacement prototype – a conversion kit for current riddling machines, for example – that is capable of handling several batches of bottles. This would provide wineries aiming to maximize their production of sparkling wine with a practical and economical solution.

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Introduction

Currently, the type of wine that has seen the greatest increase in production is sparkling wine (SW). Over the past decade, SW production has shown a steady upward trend, growing by 40% compared to just 7% for still wine (Ubeda *et al.*, 2019). SW is produced in many countries, including Spain (Cavas of Cataluña made with Macabeo, Xarello and Parellada), Germany (Riesling being the most important white grape for Sket production due to its balanced acidity, aroma, and flavor), Brazil (Chardonnay and Riesling Itálico being the main varieties), and Italy (Spumanti related to the typical aromas and production areas of native varieties). In Italy, Franciacorta, Trento DOC, Asti DOCG, and Prosecco DOC have gained significant importance (Bassi *et al.*, 2021). The production of SW involves a complex and time-consuming process, which often requires skilled manual labor and can be expensive. Different methods, such as the Champenoise, Charmat, and Asti methods, can be used to produce SW, leading to varying chemical and sensory characteristics (Sartor *et al.*, 2021). One of the most well-known methods for producing SW is the "classic method," also known as the Champenoise method. This method is considered traditional and involves two consecutive fermentation steps. The first step involves the standard production of the base wine, while the second step involves the addition of yeast, sucrose (*liqueur de tirage*), and, in some cases, a small amount of bentonite and sulfur dioxide, to the base wine, which is then bottled to undergo the final fermentation.

The wine will develop its characteristic bubbles, visible as small bubbles, as a result of the carbon dioxide produced during the secondary fermentation or "refermentation" in the bottle. After the secondary fermentation is completed, the wine is aged for an extended period, which can last from several months to several years, in contact with lees. When this period is over, the sediment will naturally move to the neck of the bottle, marking the start of the riddling or *remuage* process (Fernández-Fernández *et al.*, 2022).

The term *remuage* originates from French and refers to the process of preparing a bottle of SW for the removal of sediment. Historically, bottles are placed on specialized racks called *pupitres*, with the neck lower than the bottom, and then rotated by hand over a period of about 30 days. This causes the lees to settle at the neck of the bottle. The final step, known as *dégorgement*, involves freezing the wine in the neck of the bottle and removing the cap to allow the sediment to be expelled under pressure. The bottle is then topped off with aged wine syrup, sugar (*liqueur d'expedition*), and corked with a mushroom-shaped cork and a wire cage to prevent the cork from popping due to the pressure inside the bottle. The amount of sugar added will determine the type of SW, from demi-sec to extra-brut.

The *remuage* process has been modernized with the use of machines called *gyropalettes*. Many wineries today use automated riddling machines to carry out the *remuage* process, which reduce labor costs but require a significant initial investment. The *remuage* process using these machines takes approximately 7 days (Alexandre, 2019).

According to Torresi *et al*. (2011), these machines can be used to agitate the sediment in the bottle, reducing the time needed for this step. However, wineries that use this method may struggle to fulfill sudden increases in demand due to lengthy waiting periods. To address this issue, it is recommended to reduce the duration of the *remuage* phase. Several solutions have been proposed in the literature to shorten this process. As mentioned earlier, the *remuage* process is time-consuming, and thus many efforts have been made over the years to simplify the production process while maintaining the quality of the product.

In recent years, efforts have been made to streamline the SW production process by exploring new biotechnology methods. One such method involves using more efficient yeast strains during secondary fermentation and using immobilized yeast cells with k-carrageenan or sodium alginate (Pozo-Bayón *et al.*, 2009; Veliky & Williams, 1981). Another technique that has gained popularity in the wine industry is the use of ultrasound to accelerate wine aging. Several studies have shown that physical methods, such as ultrasound, can effectively speed up the aging process for various types of wine. The application of ultrasound technology has seen significant growth, especially in industries such as food production, pharmaceuticals, petrochemicals, and nuclear energy (Lucas *et al.*, 2009; Cruz *et al.*, 2013; Gallo *et al.*, 2018). The use of ultrasound, either alone or in combination with other treatments, is attracting much attention for its potential to produce safe foods with improved nutritional and sensory quality. Ultrasound is produced by sound waves with frequencies of 20,000 vibrations per second (20,000 Hz or 20 kHz) or higher, which are beyond the range of human hearing and can penetrate through gases, liquids, and solids. In 1993, Moyat patented an ultrasonic device aimed at revolutionizing the traditional method of producing SW. This device places the bottles in a liquid with ultrasonic transducers and utilizes an adjustable timer to regulate the immersion time, which is typically just a few seconds. The result is a reduction in the time required for the *remuage* process to less than 48 hours (Moyat, 1993). The research aimed at providing an innovative *remuage* method which is an alternative to available solutions, testing the use of ultrasonic vibration induced in the bottles via a direct mechanical coupling to speed up the *remuage* operation. Advantageously, such ultrasound generates vibrations in the bottles, which cause the lees to slide faster along the natural slopes of the glass of the tilted bottle. The combination of ultrasound and bottle inclination will cause the lees to accumulate quickly in the neck of the bottle, thus speeding up the *remuage* phase. Image analysis was applied to quantify the effectiveness of the methodology. Sensory analysis was carried out on bottles from the ultrasonic *remuage* process compared to the conventional *remuage* method. Finally, energetic aspects were indagated to provide an effective solution for wineries capable of optimizing their SW production.

Materials and Methods

The experimentation was conducted at the Department of Agricultural and Environmental Sciences of the University of Milan and led to the filing of a European patent (Remuage apparatus and method, EP3078734A1).

Prototype for ultrasonic remuage on a single bottle

The experimental ultrasonic *remuage* prototype was designed to hold one bottle in a tilted position. The prototype is designed to induce a mechanical vibration at ultrasonic frequencies in the bottle. It consists of a support element that holds one bottle and a vibrating element that is mechanically connected to the bottle. Ultrasonic vibrations are generated by the vibrating element, causing the lees to quickly move along the slope of the tilted bottle and collect in the neck. The prototype is designed to allow for a faster accumulation of the lees in the neck, speeding up the *remuage* phase. A schematic representation of the experimental ultrasonic *remuage* prototype can be seen in Figure 1.

The vibrating component is strategically placed in the bottle to induce mechanical vibrations at ultrasonic frequencies. The term “tilted position” refers to any position in which the bottle is not upright or vertical, with a “vertical” bottle defined as one resting on a flat surface with its bottom. An example of a tilted position would be a bottle lying on its side, overturned with the cork down, or in the position depicted in Figure 1. The prototype is designed to ensure a solid mechanical connection between the vibrating element and the bottle to transmit ultrasonic vibrations effectively. The vibrating element consists of a single axial transducer with ultrasonic vibrations that stresses the bottle in an axial direction relative to its longitudinal axis. In addition, a tangential transducer with ultrasonic vibration was also tested to stress the bottle in a tangential direction with respect to the circular section of the bottle sidewall (*data not shown*).

The experimental prototype features a control system designed to trigger vibration at set time intervals and/or a specific oscillation frequency. It also includes a rotation system to adjust the angle of the bottle relative to the vertical position over time. An additional control system allows for the bottle’s angle to be altered following a pre-determined schedule.

The holder component of the prototype is a passive support structure that tilts the bottle downwards, similar to the *pupitres* in the classic method. Ideally, the holder is a hollow cylinder of appropriate size that the bottle fits into, neck first and cork facing downwards, simply due to friction. The active part of the prototype is the vibrating element, which contains one piezoelectric transducer. This transducer creates ultrasonic mechanical vibrations in the bottle through a coupling flange, consisting of two semi-circular bodies that can be screwed together to embrace the bottle.

The transducer consists of two rings of piezoelectric material overlapped and fastened to each other with preloading from two metal plates. When an electric voltage is applied, the ring undergoes mechanical deformation and oscillates at a high frequency with micrometric movements, generating ultrasonic waves. The coupling flange is an aluminum ring cut in half, forming two semicircular sections that can be screwed back together, re-forming the original shape and encasing the bottle’s cylindrical body.

The *remuage* prototype enables the placement of a bottle on the support element in a tilted position relative to the vertical and induces an ultrasonic mechanical vibration in the bottle through the mechanically coupled vibrating element. In the embodiment depicted in Figure 1, the preferred embodiment of the vibration means includes a transducer that generates ultrasonic vibrations, configured to apply stress to the bottle along its longitudinal axis.

For the experimentation, the UG300W (UCE-RPC) ultrasound generator (Figure 1) was used, which is capable of converting the mains electricity at a frequency of 50 Hz into electrical energy with a frequency ranging from 20 kHz to 40 kHz). It is advantageous to combine the mechanical vibration with a gradual increase in the bottle's inclination in the overturning direction, encouraging the buildup of residue in the bottleneck and enhancing the *remuage* process. This study's prototype is well-suited for experimentation purposes, allowing verification of the impact of varying bottle inclinations and different vibration application times and modes to determine optimal *remuage* conditions. The experimental prototype is protected by a European patent (Guidetti *et al.*, 2019).

The experimental protocol for the ultrasonic *remuage* method envisaged the following steps: i) placing the bottle on the support element at an angled position relative to vertical; ii) applying mechanical vibration at ultrasonic frequencies through a mechanically coupled vibrating element. The operator can set the vibration frequency using a knob. The frequency can be set between 20 and 50 kHz. For this experimental trial, a commercial transducer with a 28 kHz vibration frequency was used. The average transducer power was set to 50 W. The bottle coupled to the support element was progressively inclined from an initial position of 26° to the vertical position of 90°, passing through 130 angles between these extreme positions. The protocol was performed by alternating 10 minutes of device activity, in which the bottle received ultrasonic stimulation and the inclination was progressively modified at regular intervals (one angular movement every 30 sec), with a 5-minute pause period, in which there was no stimulation and photographs were taken of the bottle to visualize the area covered by the residual deposit of material.

Experimental activity

The prototype has been tested, evaluating: i) the efficacy of the ultrasound treatment through image analysis; ii) the effects on the wine via sensory analysis; iii) energy consumption.

Image analysis was applied to quantify the effectiveness of the methodology. Sensory analysis was carried out on bottles from the ultrasonic *remuage* process compared to the conventional *remuage* method. Finally, energetic aspects were inspected to provide effective solutions for wineries capable of optimizing their SW production. Finally, the paper presents a SWOT analysis regarding the potential implementation of the prototype for ultrasonic *remuage* in the Champenoise method for the SW sector. SWOT is a well-known method used to highlight strengths, weaknesses, opportunities, and threats to evaluate new potential solutions. Several studies have attempted to use SWOT to analyze the implementation of solutions in the agri-food sector related to: i) procedures (Sarter *et al.*, 2010); ii) environmental impact aspects (Baudino *et al.*, 2017; Casson *et al.*, 2023); iii) technological innovation for automated systems (Giovenzana *et al.*, 2021; Pampuri *et al.*, 2021). Internal characteristics known as strengths and weaknesses provide the items a competitive edge or disadvantage. Threats and opportunities, on the other hand, are outside forces that might help or impede the creation of a product.

Evaluation of the ultrasound treatment's effectiveness

The bottle used was a 0.75 dm^3 light-colored SW "cuvee" bottle, containing Oltrepò Pavese DOCG classic method, supplied by the Torrevilla company (Torrazza Coste, Pavia, Italy) in storage at the Fontanachiara company (Stradella, Pavia, Italy) where the experimentation was conducted. The experimentation was carried

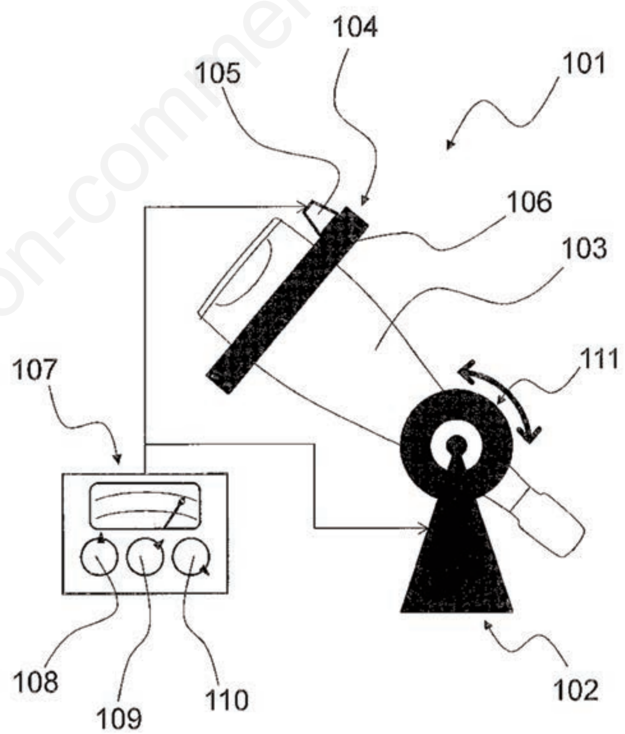

Figure 1. Experimental prototype setup scheme (Guidetti *et al.*, 2019). In detail: *remuage* apparatus (101); support element (102); single wine bottle mechanically coupled during the process (103), vibrating element (104) constituted by a piezoelectric transducer (105) and a coupling flange (106); ultrasound generator (107) with setting time knob (108), setting ultrasonic frequency knob (109), and setting rotation knob (110); rotation system (111).

out on 3 light-colored bottles, and for each bottle, at each pause period, three picture replicates were performed for the image analysis. The image analysis was performed to accurately detect and isolate the area of interest in the various laboratory photographs, namely the coarse deposit of bentonite and yeast. The same procedure was then used to monitor the progressive decrease in the deposit area during the experimental tests carried out to verify the effectiveness of ultrasound use. The image analysis was carried out using a MATLAB script, that, by supervised machine learning (SML), attributed to each pixel of the original image a class of belonging according to the colorimetric characteristics of the pixel itself (hue saturation value). The SML was set by an assignment of 206 regions of interest, randomly taken from the image gallery, with a dimension of 10´10 pixels, to one of the four selected categories (background, wine, yeast, and bentonite), using the k-nearest neighbor classification method. Each image was then subjected to analysis through the script and the result was a division of the surface into the four selected categories (Figure 2). For the determination of the area of the deposit, only the categories of yeast and bentonite were subsequently highlighted, removing any isolated pixels and including, instead, any areas surrounded by categories of interest.

Effects of the ultrasound treatment on the wine

A sensory analysis was conducted to examine the impact of ultrasonic *remuage* on SW. The study compared a SW produced with the experimental method to a conventional one made with a *gyropalette* system, with all other production factors (*i.e.*, production batch, winemaking methods, *dégorgement* process, storage, *etc.*) being equal. The evaluation was performed by a panel of 60 consumers using the triangle test (International Organization for Standardization 4120:2004 - Methodology), which is a forced-choice procedure to determine if a noticeable difference or similarity existed between the two wines. During the test, the wines were randomly presented in triads and the judges were asked to identify which wine was different. The results were analyzed using the student t-test in Statistical Package for the Social Sciences 19.0 for Windows to determine any differences in sensory scores between the samples.

Energy consumption estimation

The current prototype could be assessed as technology readiness level 3; in view of a future scale-up of the prototype, a com-

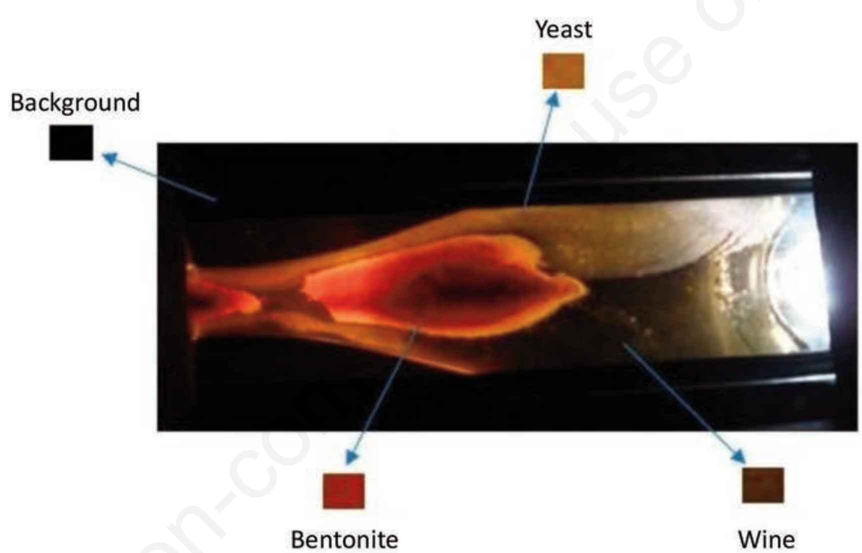

Figure 2. Examples of regions of interest assigned to the four different classes, i.e., background, bentonite, powdery yeast, and wine.

Table 1. Input data necessary for the energy analysis.

Parameters	Symbol	Units	Values
Bottles for each gy*ropalette*	n_{bott}	n°	504
Working time for *gyropalette*		days/week	7
Time for *remuage* operation for *gyropalette*		days/cycle	7
Effective time of power consumption for gyropalette		h/cycle	0.58
Working time for *gyropalette* + ultrasound		days/week	5
Number of *remuage* operations in a working day for *gyropalette* + ultrasound		cycles/day	4
Time for *remuage* operation for *gyropalette* + ultrasound		h/cycle	2.5
Effective time of power consumption for *gyropalette* + ultrasound		h/cycle	1
Specific utilization coefficient	k_u		0.7
Elettric energy cost		€/kWh	0.2
Piezoelectric transducer power	P_{pt}	W	50
Gyropallete electrical engine power		W	700

prehensive estimation of the energy requirements for the ultrasonic *remuage* operation on an industrial *gyropalette* prototype has been conducted. The *gyropalette* is designed to accommodate 504 bottles per cycle. The parameters considered for the energy estimation include the number of bottles processed by each *gyropalette*, the working time of the *gyropalette* during a cycle, the duration of the *remuage* operation for the *gyropalette*, and the effective time of power consumption during this operation. Furthermore, the study evaluated the working time required for the *gyropalette* in combination with the ultrasonic *remuage* process. The number of *remuage* operations conducted in a typical working day for the *gyropalette* with ultrasound was also taken into account, along with the time required for each *remuage* operation with the added ultrasound step and its corresponding effective time of power consumption. Moreover, a specific utilization coefficient, which indicates the efficiency of the system was proposed. Various factors such as the electrical energy cost, the power of the piezoelectric transducer responsible for generating the ultrasonic vibrations, and the electrical engine power of the *gyropalette* were also considered. Table 1 shows the input data for the energy consumption estimation.

Results

Evaluation of the ultrasound treatment's effectiveness by using image analysis

Figure 3 shows examples of images taken in a darkroom to evaluate the effect of treatment before (a) and after (b) the treatment with ultrasonic vibrations. The treatment with ultrasonic vibrations is effective during the *remuage* phase.

Figure 4 displays the kinetics of ultrasonic riddling. The nine

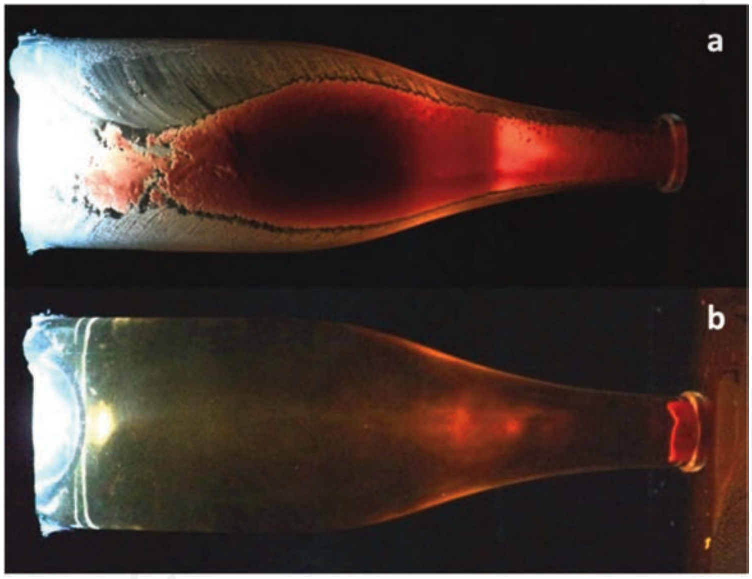

Figure 3. Examples of images before (**a**) and after (**b**) treatment with ultrasonic vibrations.

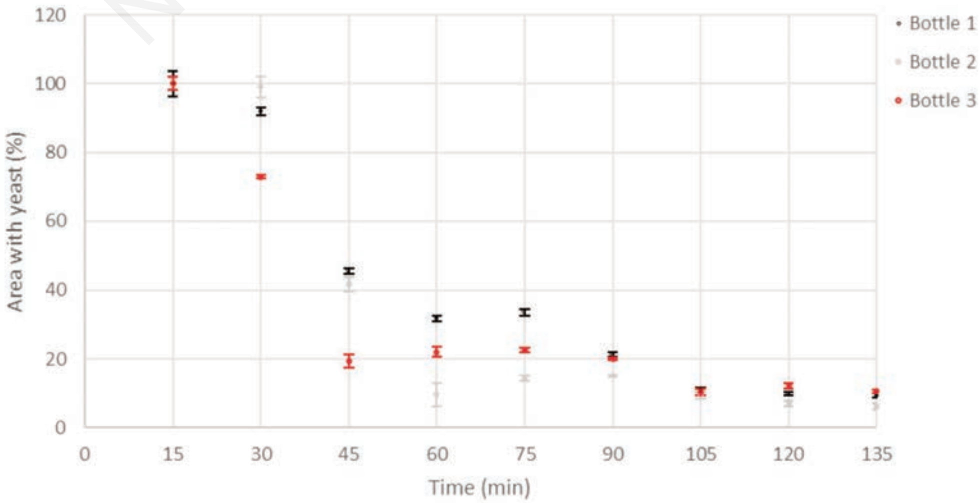

Figure 4. Area with yeast (%) is defined by image analysis of 3 bottles for 9 sampling times (0 min to 135 min) every 15 minutes.

sampling points (min) are indicated up to 135 minutes. For each sampling point, the image analysis is presented for each analyzed bottle, representing the remaining area with yeast deposit. The initial situation (*e.g.*, Figure 4) corresponds to a 100% yeast-covered area, while the final objective reached at 135 minutes for all bottles (end of the process, Figure 4) corresponds to approximately 10% of the residual area with yeast (*i.e.*, the tip of the yeast deposit). Indeed, it is evident that the three bottles show slightly different riddling kinetics at intermediate sampling points, but they eventually converge and reduce the differences in the later stages of the process (reaching the target objective) around 135 minutes (*plateau*). As expected, for each bottle and each sampling point, the variation (standard deviation) among the three photos tends to cancel out, indicating a high system stability.

Preliminary testing has indicated that the current invention significantly reduces *remuage* time. The traditional *remuage* using *pupitres* takes about 30 days, while the modern *gyropalette* method takes about 7 days. However, the experimental *remuage* prototype completed the process in less than 2.5 hours (Figure 4).

The discriminant model developed allowed obtaining a series of images in which it is possible to clearly distinguish the deposit from what should not be taken into consideration. The software was set up not to consider areas that were too small (below a threshold value) to eliminate areas surrounding the deposit but not belonging to it. The model applied to the images allowed for an accurate study of the progressive decrease in the deposit area during the experimental tests, proving the effectiveness of the tested technique.

Effects of the ultrasound treatment on wine by using sensory analysis

A sensory evaluation was performed using the triangle test (a "forced choice" technique) to ensure the desired sensory qualities as determined by the winery staff and the standard commercial product. Out of 60 judges, only 11 were able to identify the different samples. To establish significance at 99% confidence, 26 correct answers were required, and 23 were needed for 99.9% confidence (Roessler *et al*., 1978). Thus, the results showed no significant differences in sensory characteristics between the two *remuage* methods.

Energy consumption estimation

Table 2 shows the estimation data of energy consumption and cost evaluation for the *remuage* operation with and without ultrasonic assistance on a *gyropalette* system. For the traditional *gyropalette* the power required is 0.70 kW, whereas, with the addition of the ultrasonic system, the total power increases significantly to 18.34 kW. This substantial rise in power is primarily attributed to the power consumption of the ultrasonic system, which accounts for 17.64 kW.

The energy consumption for the *remuage* operation in traditional *gyropalette* is quite low at 0.41 kWh per cycle, but when the ultrasonic system is incorporated, the energy consumption per cycle rises to 18.34 kWh. This drastic increase is proportional to the additional power required for the ultrasonic process. Consequently, in a typical week, the energy consumption for *remuage* in traditional *gyropalette* reaches 0.41 kWh, while the *gyropalette* with ultrasonic assistance consumes a substantially higher amount of 366.80 kWh.

To understand the specific energy consumption per bottle, the total energy consumption is divided by the number of bottles treated. In traditional *gyropalette*, the specific energy consumption is relatively low at 0.001 kWh per bottle, while it rises to 0.036 kWh per bottle with the inclusion of ultrasound assistance. This difference indicates that the ultrasonic *remuage* process is more energy-intensive compared to the traditional method.

The specific energy cost for *remuage* is calculated based on the energy consumption and the cost of electricity, which is envisaged at 0.20 €/kWh. In traditional *gyropalette*, the specific energy cost is remarkably low at 0.0002 € per bottle, while in *gyropalette* with ultrasound, it increases to 0.0073 € per bottle. Consequently, the *remuage* operation incurs a higher cost when ultrasonic assistance is employed. Overall, the simulation highlighted the impact of incorporating the ultrasonic system into the *gyropalette* for the *remuage* process, resulting in higher energy consumption and associated costs. However, the use of ultrasonic assistance may provide benefits in terms of efficiency and effectiveness, making it essential to strike a balance between the added costs and potential advantages in the winemaking production process. Furthermore,

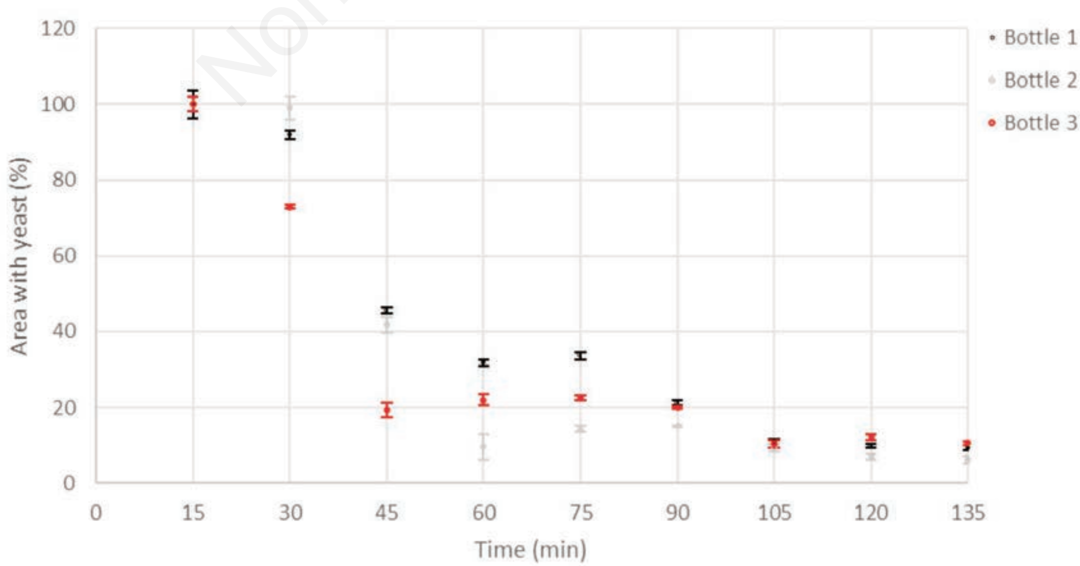

Figure 4. Area with yeast (%) is defined by image analysis of 3 bottles for 9 sampling times (0 min to 135 min) every 15 minutes.

an ultrasonic *gyropalette*, being able to process a very high number of bottles comparable to the traditional one, would also bring undoubted advantages from the point of view of space, effectively reducing the need to use large spaces of the cellar for the *remuage* operation, as well as reducing the stay of the bottles in these rooms, *e.g.*, a company that does subcontracting, equipped with such a device, could potentially complete a consignment that arrived in the day, without the need to store large quantities of bottles in the warehouse.

The initial experimental results showed the viability of the tested *remuage* prototype and method. The aim is to also provide a *remuage* prototype and method that can process multiple bottles simultaneously. A future goal could be to create a kit that can convert a *gyropalette* machine, including at least one support element designed to hold bottles at an angled position relative to vertical. This kit should be compatible with existing *gyropalette* machines through the addition of a mechanically connected vibrating element. This conversion kit will transform *gyropalette* machines into effective and efficient *remuage* prototypes as per the present research. It also allows the use of existing *gyropalette* machines, saving the cost of purchasing new equipment. This solution could be particularly suitable for industrial use, like in a winery where many bottles require *remuage* treatment. The design of a potential prototype will be similar to that of a *gyropalette* machine, improved based on the present study (Figure 5). The *remuage* prototype should be based on a support element designed to hold multiple bottles at an angled position, similar to traditional *gyropalette* machines. The prototype will include a multi-bottle vibrating plate

Table 2. Energy consumption estimation results.

Parameters	Symbol	Units	Gyropalette	Gyropalette + ultrasounds
Electric energy consumption evaluation				
Ultrasound system power	P_u	kW	/	17.64
Gyropalette power	P_{gy}	kW	0.70	0.70
Total system power	P_s	kW	0.70	18.34
Energy consumption for remuage operation	EE	kWh/cycle	0.41	18.34
Number of remuage operations in a week		cycles/week	1	20
Bottles treated in a week		n/week	504	10080
Energy consumption for *remuage* operation in a week	EE	kWh/week	0.41	366.80
Specific energy consumption		kWh/bottle	0.001	0.036
Cost evaluation				
Energy consumption	E_{tot}	kWh/bottle	0.001	0.036
Specific energy cost		€/kWh	0.20	
Specific energy cost for *remuage*		€/bottle	0.0002	0.0073
Production cost		€/bottle	3.00	
Incidence *remuage* operation		%	0.005	0.243

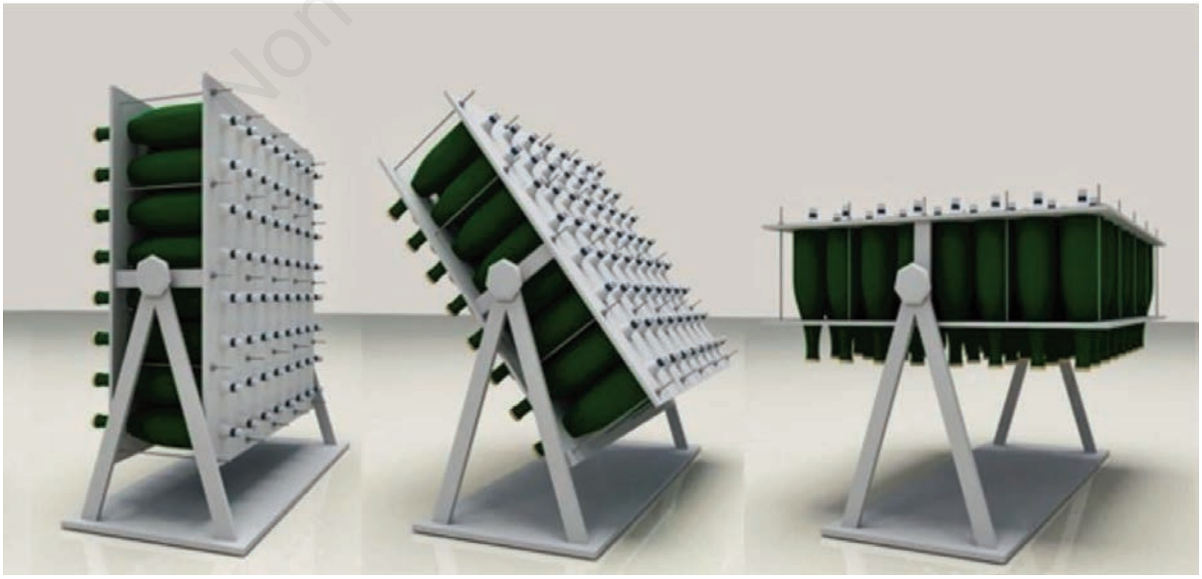

Figure 5. Rendering of a possible solution for the application of piezoelectric transducers on many bottles.

Table 1. Strengths, weaknesses, opportunities, and threats from research outputs in view of the application in the Champenoise method for the sparkling wine sector.

	Internal		
	Strengths	**Weaknesses**	
Positive	Speed of treatment. No impact of the treatment on the sensory characteristics of the wine. Patented solution at the European level. Limited increase in energy consumption.	Variability in the shape of the bottle can reduce the effectiveness of the treatment. Variability in the mix of adjuvants for the removal of yeasts in the bottle. Device for one bottle, not yet engineered for many bottles at the same time.	**Negative**
	Opportunities	**Threats**	
	Better process management. Better warehouse management. Productivity increase. Reduction of production costs. Potential *remuage* without adjuvants for sustainable products. Potentially applicable to turntables already used in wineries.	Difficult adaptability on turntables. Greater installed power. Strong link with traditional methods by wine operators. Reduced orientation towards innovation by wine operators.	
	External		

with multiple vibrating transducers applied to it. A scale-up study will be useful to define the proper number of transducers.

The prototype will also be equipped with rotating capabilities to change the angle of the bottles relative to vertical over time by turning the basket, preferably using electric motors (not shown).

SWOT analysis

To summarize the strengths, weaknesses, opportunities, and threats from research outputs in view of the application in the Champenoise method for the SW sector, a SWOT table was proposed (Table 3).

The new potential solution consisting of a prototype ultrasound for the *remuage* process, exhibits internal strengths, such as its rapid speed and the preservation of the wine's sensory characteristics. Additionally, it holds a patented solution at the European level and has a limited impact on energy consumption. However, it faces internal weaknesses, including variability in bottle shapes that may reduce treatment effectiveness and variations in the mix of adjuvants for yeast removal. Moreover, the current device is designed for one bottle, lacking engineering for the simultaneous treatment of multiple bottles.

Concerning external factors the implementation of the ultrasound prototype presents opportunities for better process and warehouse management, productivity increase, and reduced production costs. According to Agenda 2030, related to green production, the prototype also opens the possibility of sustainable products through *remuage* without adjuvants. Moreover, there is potential applicability to *gyropalette* already used in wineries hence the possibility of reusing technology traditionally implemented in the *remuage* process. On the other hand, threats include challenges in adapting to *gyropalette*, requiring greater installed power. Additionally, there may be a strong link with traditional methods favored by wine operators, potentially reducing their orientation towards innovation.

Conclusions

In modern wineries, the *remuage* process is often automated using *gyropalette* to reduce manual labor costs. However, the process duration of approximately 7 days and the substantial initial investment present challenges, especially during sudden increases in bottle demand. This study proposes an innovative method utilizing ultrasonic vibrations to accelerate the *remuage* process, approximately 2 hours. The method showed significant time savings without compromising the wine's sensory qualities, leading to a European patent. This scientific investigation lays the groundwork for optimizing energy consumption in the winemaking industry and may aid in the development of sustainable and cost-effective *remuage* techniques for large-scale wine production. A cost-effective and efficient solution for optimizing SW production is envisaged by developing a versatile *remuage* prototype to handle single or multiple batches of bottles. The ultrasound prototype for the *remuage* process has internal strengths in terms of rapid speed, preserving wine sensory characteristics, and holding a patented European solution with low energy consumption. However, internal weaknesses include bottle shape variability and limited adaptability for multiple bottles. Externally, the prototype offers opportunities for improved process management, reduced costs, and sustainable production as envisaged in Agenda 2030. Still, challenges lie in adapting to *gyropalette* and potential resistance from wine operators towards innovation.

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