

Microfluidics and the Spirits Industry: A Review

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There is and will always be the need to provide authentic and safe alcoholic beverages. To achieve this goal, researchers are constantly looking for innovative and practical approaches to analyze their samples and control their quality. Quality control can be challenging in the spirits industry due to their production (mashing, fermenting, distilling, aging, packaging) and their complex chemical composition. To assess the quality and safety of alcoholic beverages, a variety of analytical procedures have been developed and are currently in use. Although these laboratory-based approaches offer a high level of sensitivity, they can be both time-consuming and costly. Therefore, it is an ongoing need to advance simpler, faster, more precise, field-deployable, and more sensitive instruments to identify chemicals and abnormalities in alcoholic beverages. We believe many needs can be addressed using microfluidic technologies, sometimes referred to as lab-on-a-chip devices. In this review, we will discuss recent significant advancements in microfluidics for the assessment of alcoholic beverage products. The analysis and viewpoints presented in this study are intended to stimulate continued development of microfluidic devices in the spirits sector and other food safety testing and monitoring fields, benefiting human health and overall well-being.

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INTRODUCTION

Food composition and its impact on health have produced a need for improved quality control in order to provide authentic and safe alcoholic beverages. To achieve this goal, researchers are constantly looking for innovative and practical approaches to analyze their samples and control their quality.

Controlling liquor quality is a significant challenge in the spirits manufacturing industry. The amount of ethanol (ethyl alcohol) in spirits is a significant aspect of assessing its overall quality [1-3]. Besides ethanol and water, organic molecules, namely organic acids, aldehydes, esters, higher or lower order alcohol, and many other compounds, may be present in alcoholic beverages during the brewing, maturation, or distilling process [4]. All these compounds directly affect the quality of the alcoholic beverages in different ways. Thus, to ensure the quality of different spirits, it is very important to determine the quantity and presence of different compounds, including unwanted hazardous material.

To ensure the quality and safety of alcoholic beverages, a number of analytical techniques for the examination of spirits components in either the gas and/

or liquid phase are currently in use. This includes gas chromatography [5-7], high performance liquid chromatography [8,9], mass spectrometry [10-12], infrared or UV-vis spectrometry [13,14], and solid-phase microextraction [15,16]. Although these laboratory-based approaches offer a high level of sensitivity, they can be time-consuming, requiring trained personnel, and can use expensive equipment. Further, many distilleries lack modern analytical equipment and typically use the analytical services of an outside laboratory. Here, findings can take anywhere from some hours to many days, compromising productivity.

As a result, there is an ongoing need to create simpler, faster, more precise, field-deployable, and more specific devices for detecting substances in alcoholic beverages in order to ensure quality, avoid adulteration, and ensure safety. We believe many needs can be addressed using microfluidic technologies, sometimes referred to as lab-on-a-chip devices. In this review, we will provide a brief introduction to microfluidics and later describe several microfluidic studies associated with the spirits industry, with an emphasis on analytical techniques and monitoring various target compounds that are important to the quality and safety of alcoholic beverages.

We will also address how microfluidics can aid in fermentation, maturation, identification, and verification of alcoholic beverages.

MICROFLUIDICS

INTRODUCTION

Microfluidics is an interdisciplinary field where a small sample of fluid is transported and analyzed within a miniature device, typically requiring microliters (or less) of the sample. In 1979, the foremost microfluidic technology for gas sensing was created on a wafer made of silicon. It comprised a thermal conductivity detector coupled with a gas chromatograph, a capillary column, and a sample injection system [17]. Ever since, microfluidics has expanded into a variety of domains, including chemistry, biology, medicine, and physical sciences. Microfluidic devices have several benefits, including decreased amount of reagents needed, less waste, and measurement automation [18]. When compared to macroscopic systems, microfluidic devices can perform processes faster while using far fewer chemicals and solvents [19]. The technology allows laboratory testing to be completed in a fraction of the time, varying between hours and minutes, using chemicals as small as microliters or nanoliters. As a result, energy consumption and waste generation are minimized. Owing to its unique properties of microfluidics' small dimensions, which result in a greater surface area-to-volume ratio, elevated surface tension, laminar flow, and improved capillary effects, microfluidic systems have enormous potential for miniaturizing and enhancing existing methods for particular detection, target separation, and assessment [20]. Additionally, advantages such as mobility, sufficiently large sample detection, and a variety of configurations for numerous operational modules are available [21-24].

Microfluidics have been used successfully for a plethora of health science applications, including cell manipulation, sorting, and separating; identification of pathogens, antibodies, and viruses; analysis of secreted compounds, detection of biomarkers, and many more [25]. Microfluidics also has a significant presence in the pharmaceutical industry, including the synthesis of new drugs, drug screening, and the impact of drug dosage on biological samples. Paper-based microfluidic devices have also been used for drug analysis and environmental monitoring [26,27]. Microfluidics have also been used for quality control and analysis in food sciences. For example, devices can monitor a variety of target substances, including chemical hazards and other contaminants detection as pesticides [28]. Microfluidics have also been used to assess emulsifications, quantify nutritional or toxic compounds, detect food pathogens, etc. [29,30].

Microfluidic platforms either pump or wick a stream of fluid-(s) through the device or generate and manipulate a series of micro-droplets, the latter referred to as digital microfluidics. Small micro-channels within a device are sometimes referred to as capillaries. Capillary microfluidic systems control the speed and direction of flow by using positive pressure generated by syringe pumps, pressure pumps, gravity, or other approaches [31]. The applied pressure overcomes resistive surface tension and hydrodynamic resistance within the device. If the micro-channel is hydrophilic, then surface tension may wick fluid into the device. Because of current fabrication practices, many microfluidic systems are planar and have channels with rectangular cross-section. Systems can be categorized by how they intersect with other channels, including T-junction [32], Y-junction [33], or cross-junctions [34]. Through careful manipulation of the fluid streams, liquid samples can be under hydrodynamic focusing [35] which can enhance some sensing applications, including flow cytometry. If the fluid streams are immiscible, then droplets can be created and analyzed individually [36] for a rapid analysis of isolated samples. Paper-based microfluidic system is a more recent advancement, using hydrophilic cellulose or other fibers to transport the fluid to different sections of the device, eliminating the need for external pumps [37].

FABRICATION

Microfluidic devices have been manufactured in a variety of ways [38]. Many micro-channel features are sub-millimeter, and such features can be created using a variety of additive or subtractive mechanical, chemical, laser-made, or other types of processes [39]. Materials include ceramics, glass, metals, silicon, elastomers, and thermoplastics. However, the most prominent method for creating microfluidic devices is termed "soft lithography". Soft lithography refers to molding elastomers, which are typically polydimethylsiloxane (PDMS). First, microfluidic features, generally from 10 μm to 1,000 μm in height are patterned on a substrate using photolithography, with Su-8 being the most often used photoresist [40]. Next, an uncured polymer is poured onto these features and a vacuuming is utilized to remove bubbles and for the polymer to conform around the microfluidic features. After curing, the piece is took off the master mold and sealed onto a glass or polymer substrate [40]. In soft lithography, the master mold can be used repeatedly to create many polymer castings of the device. If microfluidic mold features are created from more rigid materials like silicon or metal, the master could be used for hot embossing [41] or injection molding [40,42]. Even though a majority of microfluidic chips are created from polymers, glass-based fabrication methods can be used [43] when its chemically inert properties are favorable

for sample analysis.

The 3D printed microfluidic device is considered the most current innovation in microfluidic technology [44,45]. By selectively curing, depositing, or combining materials in consecutive layers in 3D printing, digital models of microfluidic systems can be created while minimizing waste [46]. Most 3D printed structures are from thermoplastics, but Gal-Or et al. [47] created glass microfluidic devices with dimensions down to 100 μm with outstanding optical quality in tens of minutes using molten soda-lime glass.

EXAMPLES OF MICROFLUIDICS FOR THE SPIRITS INDUSTRY

There are several characteristics of microfluidic analytical devices that can be helpful for the spirits industry. This section highlights several applicable studies and approaches.

FERMENTATION

The yeast *Saccharomyces cerevisiae* uses fermentable carbohydrates to make ethanol, carbon dioxide, and other metabolites, many of which add to the flavor of the alcoholic beverage. As a result, selecting a good yeast is critical for any distillery. Contamination by a range of microorganisms, particularly lactic acid bacteria and wild yeasts, can compromise the final product. But traditionally, little thought was given to this selection, and a locally sourced spent brewing yeast would be used for whisky

fermentations. Yeast was readily available, and it was inexpensive and simple to procure and use. However, more specialized distilling yeasts with a higher ethanol tolerance and a wider substrate range are more prevalent as a replacement for leftover brewing yeast and are occasionally (but not always) blended with the brewing yeast [48]. Microfluidics could be useful in industry for the selection, and sorting of yeast; several microfluidic approaches to monitor, analyze, and sort yeast are described next.

Within a microfluidic device, long-term cell cultivation under different substrate concentrations, i.e., glucose concentrations with individual yeast tracking are achievable. Oliveira et al. [49] demonstrated that selecting growth profiles of free cells using a concentration gradient microfluidic device based on diffusion is an excellent technique for analyzing the growth of *Saccharomyces cerevisiae* at various concentration of glucose. To create the gradient on the bottom level, 0 g/L and 40 g/L solutions of glucose were injected, and for ten hours, *S. cerevisiae* growth was observed using time-lapse confocal microscopy along with 30-minute picture acquisition frames. Traditional batch cultivation experiments were also performed to compare the results that showed a similar pattern. Thus, the development of a diffusional concentration gradient enabled researchers to analyze cell behavior across a range of glucose concentrations in a single assay. The kinetic Monod variables were also calculated utilizing low concentrations, which are inaccurate in batch methods due to the limited substrate's consumption over time, making this a more practical and time-efficient procedure than typical submerged

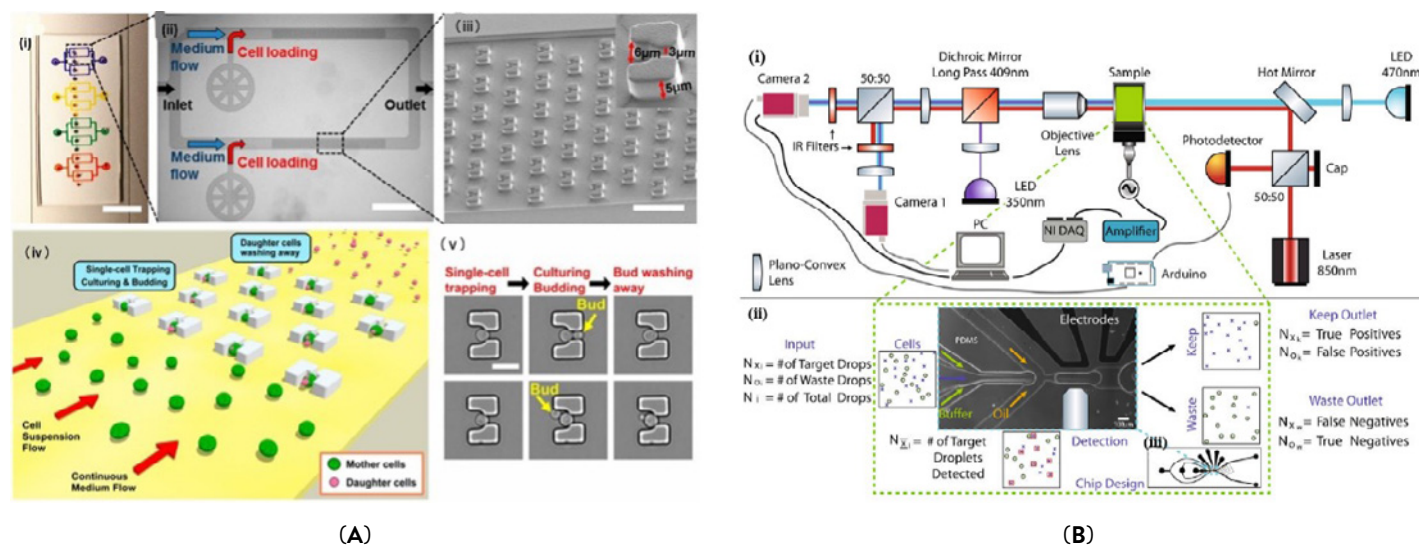


FIGURE 1 Yeast aging study and yeast sorting using microfluidics. (A) Design and working mechanism of microfluidics chip (i) Optical representation of the device. (ii) Branched trapping channels. (iii) SEM image of trap arrays (iv) Schematic diagram of working mechanism. (v) Single yeast cell showing the mechanism of action. (Scale bar: 10 μm). Reprinted with permission from [50]. (B) Schematic representation of the two-phase microfluidic device. (i) schematic of dual-imaging microscopy system. (ii) Cell sorting performance characteristics are defined. (iii) Three inlets and two outlets completed the chip. Reprinted with permission under a Creative Commons Attribution-NonCommercial 4.0 International License from [57] (<https://doi.org/10.1038/s41598-020-65483-2>)

cultivation procedures.

Besides growth rates, the complete lifespan of yeasts, as well as morphological and phenotypical changes in aging, are all factors to consider when choosing the right yeast strain for beverage fermentation. As illustrated in Figure 1A, Jo et al. [50] established a high-throughput yeast aging study chip microfluidic device capable of trapping up to 8,000 separate yeast cells while excluding newly budded daughter cells. They assessed changes in cell morphology and attributes associated with lifespan, including essential cell size, protein subcellular localization, and terminal morphology. This platform enables cells to be held and analyzed under a steady growth setting for the entirety of their life within the microfluidic channel, mitigating the impacts of operator and environmental fluctuations. Existing lifespan analysis have hampered large throughput aging investigations in yeast, but these capabilities substantially remove those constraints. To get more ideas and more research about yeast aging, we refer to the reader a review of articles on yeast aging studies using microfluidic devices [51]. As per their findings, to the present, several microfluidic devices have effectively shown the ability to follow the whole yeast replicative lifecycle according to the researchers [52-56].

Microfluidics can sort yeast cells depending on a variety of parameters. Keinan et al. [58] used a technique that balanced shear-induced forces with other hydrodynamic forces within a curved channel to sort larger yeast. Young and adult populations of yeast were isolated by 107 cells/min/channel rate from mixed populations. The technology is effective for high flow rates, preventing clogging and increasing throughput, and it can sort yeasts in the spirits sector [59]. Their method allows for large-scale separation of microbes based on minute size differences ($\pm 1.5 \mu\text{m}$), which is unsurpassed by other technologies [60,61]. They discovered that expression of recognized yeast age markers can fluctuate far sooner than previously reported, after two to three budding events, utilizing this technique and a newly devised algorithm for evaluating bud scars [62]. According to mass spectrometry analysis of sorted yeast populations, the proteomic patterns of young and adult cell populations derived from the same colony varied considerably in terms of expression of youthful and aging markers.

A microfluidic procedure was performed in another study to differentiate and separate genetically similar yeast strains dependent on adhesion strength [63]. Different yeast strains have different strengths which can distinguish them from a mixed cell population. They showed the technique's efficacy by measuring the differential adherence of nine commonly used *S. cerevisiae* laboratory variants and mutations lacking fungal adhesion-related FLO family genes. They determined that the solution's ionic strength

and the substrate's hydrophobicity influenced yeast adhesion.

As illustrated in Figure 1B, Sesen et al. [57] presented a two-phase microfluidic system. The system is capable of real-time imaging within droplets during flow. Even though the process is based on droplet sorting, it is rather adaptable and hence has the potential for yeast sorting. The acquired digital images were processed to determine which cells should be sorted depending on programmable/adjustable attributes. Sorting is done by the application of an electric field to induce a force called dielectrophoresis [64,65]. To demonstrate the system's capabilities, it is configured to handle the Poisson loading problem by filtering for droplets carrying a single 85 percent pure red blood cell. Additionally, utilizing fluorescence imaging and machine learning, single K562 cells were put into clusters depending on size and circularity. Yu et al. [66] demonstrated sorting yeast cells based on their morphological characteristics using this image processing technique, as previously indicated. Because pictures take longer to gather and analyze, the detection rate is quite slow (12 cells/minute).

Microbiological contamination detection is crucial for quality control in the brewing industry, as it can result in significant recalls and impairment to the brand's reputation. Condina et al. [67] proposed a novel, low-cost strategy for the high-throughput and useful separation of yeasts (*S. cerevisiae* and *S. pastorianus*) from beer spoilage bacteria (*Lactobacillus brevis* and *Pediococcus damnosus*) using inertial microfluidics and flow separation in a spiral microchannel. They exhibited high-throughput, rapid separation of spoilage bacteria of size 0.3–3 μm from background yeast of around 5 μm with an efficiency of 90 percent. This system could be linked into the manufacturing process, enabling real-time assessment of beer spoilage and rapid response to contaminant breakouts in the brewery.

Other than yeasts, different factors are important to be considered for the fermentation process monitoring. Microfluidics along with different sensors can do measurement of various components in fermentation, such as ethanol, potassium, carbon dioxide, acetoin. An overview of those is shown in Table 1.

One study combined microfluidics with potentiometric detection for monitoring total potassium in winemaking operations without sample preparation [68] with a good limit of detection (LOD), reproducibility, and repeatability (Table 1). These characteristics make it ideal for ongoing monitoring of total potassium levels in wineries, particularly throughout critical stages of the fermentation process such as grape cultivation/reception, fermentation, and final product quality standards. As the system does not need any sample pretreatment, this automated system has at least four months lifetime for repetitive analysis. Applying

TABLE 1 Fermentation process parameter monitoring using microfluidics.

DETECTED COMPONENT	DETECTION METHOD	LIMIT OF DETECTION	REFERENCE
Potassium	Microfluidics with potentiometric detection	$75 \pm 12 \text{ mgL}^{-1}\text{K}^{-1}$	[68]
Carbon dioxide	Microfluidics, gas diffusion module along with optical flow cell	83 mgL^{-1}	[69]
Acetoin/Diacetyl	Sensor with enzyme acetoin reductase	10-100 μM	[70]
Hexoses (glucose & fructose)	Electrochemical sensors	0.105 μM	[71]
Ethanol concentration	Microfluidic membrane device	13.0 vol% at 25 °C and 7.8 vol% at 30 °C	[72]
pH	Microfluidics with pH sensing membrane	5 M [H^+]-pH 3.0 and pH 6.0-2 M [OH^-]	[73]

a pH-sensitive acceptor solvent, the same group proposed a low-cost cyclic olefin copolymer-based microsystem with an integrated gas diffusion step for spectrophotometric CO_2 detection in wines and brews [69]. The technique applied to the real samples and hydrodynamic variables with a range from 255 to 10,000 mg/L of CO_2 and a LOD of 83 mg/L with a sampling rate of 30 samples per hour.

Another study described a capacitive electrolyte-insulator semiconductor field-effect biosensor for detecting acetoin [70]. The sensor can monitor the pH change because of the enzymatic dehydrogenase. The detection concentration range of acetoin is between 10 μM and 100 μM , measured in a buffer solution of pH 7.1. López-Fernández et al. investigated the potential of thin film electrodes made by the combination of copper-cobalt oxide compiled in a single step via vapor deposition and made a non-enzymatic electrochemical sensors for hexoses (glucose plus fructose), as well as the feasibility of using such a system for fermentation process monitoring [71]. Films with a Co/Cu atomic ratio of 3.4 had a sensitivity 0.710 A/M-cm², a small LOD of 0.105 μM , and remained stable at long storage periods, according to this study. The capabilities of this electrocatalytic sensor were examined for synthetic wine fermentation process, with promising results for in situ monitoring. Lu et al. [73] developed a pH detection device based on a microfluidic chip that can measure pH levels in extreme acidic and alkaline situations in real time. A pH sensor membrane, as well as a light source and photodiode, were used along with a microfluidic chamber to create the sensing chip. The amount of light that was transmitted changed as the pH of the fluid changed. The designed pH sensing chip has a response time of 90 seconds and works in the pH ranges of pH 3.0 (5 M [H^+]) to pH 6.0 (2 M [OH^-]), making it suitable for on-line monitoring.

Lopes et al. [74] developed and validated a 3D printed millireactor with passages loaded with yeast trapped in

alginate hydrogel for alcoholic fermentation. The best millireactor configuration was a 2% of alginate solution with 25 g/L cells, which produced 11.24 ± 0.015 g/L of ethanol on average, with a productivity of 22.49 g/L-h and a 44% efficiency. They've established that their technology and procedures are viable alternatives for fermentation, outperforming millireactors with free cells. Further, a technique for detecting or monitoring ethanol concentration during fermentation can influence production efficiency. By constructing a responsive microfluidic membrane device with a layered ethanol-sensitive barrier in a "stamp-like" manner, a novel approach of ethanol concentration was established for online monitoring [72]. The microfluidic membrane devices exhibit key interactive ethanol concentrations around 10% at temperatures below the volume phase transition temperature, e.g., 13.0% by volume at 25 °C and 7.8% by volume at 30 °C and could be connected to a practical ethanol production or separation system for ethanol concentration monitoring. The device possesses properties of reversibility, repeatability, high stability and long lifetime, which may benefit industry where monitoring a quick shift in pH benefits online pH detection systems.

MATURATION

One of the crucial elements impacting distillation quality of the product is the transformation of lignin into non- or low-volatile phenolic compounds during maturation. The presence of atypical or abnormal amounts of these compounds may indicate that the aging was induced artificially or may indicate some type of adulteration [75]. As a result, profiling those lignin-derived phenolic chemicals that can signal aging as well as cask diversity in the maturation process is critical. High performance liquid chromatography (HPLC) was chosen as the best method for analyzing the low-volatility chemicals created throughout the aging

process [76]. This approach has been used to measure low molecular weight phenolic chemicals in aged wine brandies, such as phenolic aldehydes and acids [77,78]. To identify both volatile and non-volatile chemicals created during spirit maturation, gas chromatography mass spectrometry (GC-MS) and liquid chromatography mass spectrometry (LC-MS) have been used [79-81]. One of the key unsolved difficulties is identifying chemicals that are important in distinguishing spirits of different eras. To identify aged wine distillates and other spirits, the ability to evaluate non- or low-volatile phenolic compounds quickly and precisely is critical. Microfluidics, along with different sensing mechanisms, could be useful for quick and efficient identifications of aging markers.

Microfluidics coupled with electrophoresis or other sensing methods can measure phenolic chemicals and assess the impact of aging. Among them, capillary electrophoresis (CE) is the most popular, defined as an electrokinetic separation technique that uses an electric field and a small capillary tube to separate molecules or ions [82]. Capillary electrophoresis is a well-established technique for regular examination of inorganic and organic ions, short-chain organic acids, carbohydrates, etc. [83-85]. In one study, four different phenolic aldehydes (syringaldehyde, sinapaldehyde, vanillin, and coniferaldehyde) and five distinct phenolic acids (ferulic, syringic, vanillic, p-coumaric, and p-hydroxybenzoic) were identified in aged brandy and wine and were separated using capillary zone electrophoresis [86] and a variable wavelength UV detector [87]. The total amount of such chemicals increased with age. The sum of syringic and vanillic acid concentrations can characterize products by their aging level. However, no consistent rise in aromatic acids has been detected in distillates older than 25 years. In whiskies, White et al. [88] employed a similar approach of capillary electrophoresis with UV detection. They looked at how the phenolic acid profile of three types of Irish whiskies was affected by aging length, aging process, and whiskey mashbill: different types of whisky from the same distillery, single malt whiskies matured in different casks within the same distillery, and a range of single pot still whiskies unique to Ireland. As with the previous study, aging had a beneficial effect on the levels of phenolic acids found in whiskies. In addition, the variety of phenolic acid compounds in the finished whiskies was influenced by the casks used, with sherry casks having the most phenolic ingredients.

To assess Scotch whisky age and barrel type, researchers used UV-Visible spectroscopy and low-powered ultrasonic characterization [89]. The variation in compressibility of the complete sample, which includes congeners in the maturing spirit, is assessed using the speed of sound, which can be used to identify the age of various samples

(Fig. 2A). UV-Visible spectroscopy was used to check the Scotch whisky cask type. Additionally, it was detected alternatively aged ones meaning the maturation was done unconventionally or reflect some form of adulteration [75] because they have different peaks with congener profiles. According to spectrophotometry, the antioxidant content in Scotch whiskies increase with age but may decrease with alcoholic strength. Although this study was not conducted on a microfluidic device, the underlying physics can be adapted to that scale; for example, acoustic microfluidic devices [90] have been used to manipulate and characterize samples.

Wei et al. [91] used a convenient electronic nose (E-nose) with a sensor comprised of an array of 12 "metal oxide sensors" to recognize rice wines of various ages. The sensor chamber had an inlet and an outlet, and a sample was poured in through the inlet. The wines' VOCs were then detected by circulating in a closed loop channel, as shown in Figure 2B. A wireless connection module was used to send the obtained response values to a smartphone. Sensors can detect ammonia, methane, butane, propane, trimethylamine, methyl mercaptan, and other volatile organic components, which can be utilized for categorization and prediction analysis. To categorize data, various data processing algorithms were utilized, including principal components analysis (PCA), locally linear embedding (LLE), and linear discriminant analysis (LDA) [94-96]. To anticipate different marked ages of the wines, partial least squares regression (PLSR) and support vector machine (SVM) were applied as machine learning algorithms [97,98]. With a greater correlation ($R^2 = 0.9942$) and a smaller root-mean-square error (RMSE = 0.0404), the SVM approach provided the maximum accuracy of the taste set of rice wine samples. They conducted the tasting at the lab's constant temperature, ignoring the temperature fluctuation impact that is essential for wine factory testing. Overall, because of its tiny size and portability, it is a workable solution that should be examined further.

Gustatory and olfactory sensor systems were built and utilized to categorize vinegar samples with varied indicated ages in another study [99]. They combined two sensor systems to cover a wider range of chemicals than a single sensor system could. With the use of PCA and LDA, the signal of sensor arrays was changed as the VOCs in vinegar varied during storage. In this study, the PCA and LDA both have a high classification rate of vinegar (up to 100%), leaving the possibility of identifying wine and other spirits with varied marked ages.

In a different experiment, Prat-Garca et al. [100] proposed a method for detecting the distribution of O_2 content and its changes throughout the interface and adjacent liquid of oak wood pieces soaked in a model wine by employing

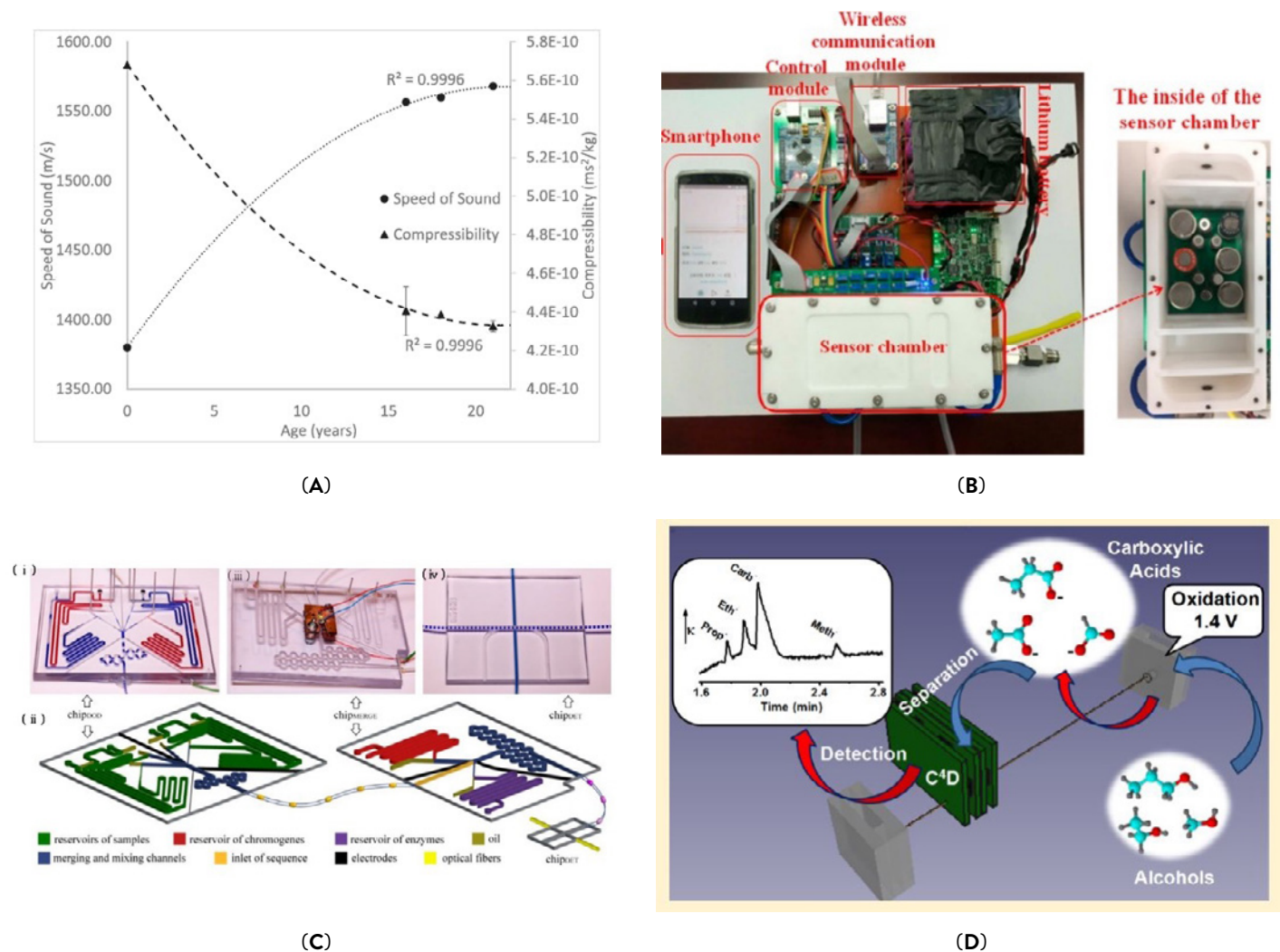


FIGURE 2 (A) Speed of sound and compressibility variation for whisky with age (Sample ID 16, 18, 21). Different value for distinctive ages. Reprinted with permission from [89] (Copyright 2020 John Wiley and Sons) (B) The setup of the system showing the sensor chamber. Adapted with permission under a Creative Commons Attribution-NonCommercial 4.0 International License from [91] (<https://doi.org/10.3390/s17112500>). (C) Detailed illustration of the microfluidics chip. (i) Chips for generating droplets (ii) Droplet storage for incubation process (iii) ChipMERGE for merging the droplets (iv) ChipDET for measuring concentration. Reprinted with permission under a Creative Commons Attribution-NonCommercial 4.0 International License from [92] (<https://doi.org/10.3390/mi6101435>). (D) Methanol detection using capillary electrophoresis coupled with conductivity detection. Reprinted with permission from [93] (Copyright 2017 American Chemical Society)

O₂ responsive nanoparticles and an RGB camera. With a constant oxygen content in the nanoparticle solution, the system was calibrated. The oxygen optode probe device may then monitor the variation in the model wine once the oak wood is inserted in the measuring cell. The kinetics of oxygen transfer-consumption in a wood soaked in a model wine were depicted by altering the exposure period in both the regions adjacent to the wood and the liquid itself. Furthermore, because of the high resolution of the digital images, the differential release of O₂ from distinct parts of the wood could be seen. The slow and continuous diffusion of oxygen from wood piece occurs and sustains the processes involved with wine aging, and this research aids in visualizing the dynamic behavior of wood degassing and oxygen absorption. Thus, this system could compare the

behaviors of different areas in the same wood sample, enabling a straightforward method of analyzing the complex interaction of spirits with oak.

DRINK IDENTIFICATION & AUTHENTICATION

Because rebranding low-quality commercial whiskeys as premium products may be extremely damaging to a producer, maintaining the safety and quality of alcoholic beverages is a constant concern. Chemical analysis has been used to evaluate and authenticate the quality of food and beverages. Contaminated and/or fraudulent items will have a considerably different composition [101,102].

Ethanol concentration

Primary alcohol (ethanol) determination is a significant characteristic in the fermentation industry, determining not only product yield and quality, but also its potential value. For a variety of reasons, including statutory labeling of ethanol content for tax purposes, local government-imposed public policy, and even religious considerations, precise and accurate measurements of ethanol is essential to preserve the quality and features expected by customers.

Microfluidics along with other separation and detection technique such as capillary electrophoresis and UV light can be used for quantification of alcohols in drinks. Table 2 summarizes this information. Rezende et al. [103] announced for the first time the implementation of a method for quantifying the alcoholic percentage in whiskey samples using micellar electrokinetic chromatography (MEKC) [104] on microchips in combination with the contactless conduction detection method. Ethanol, butanol, and pentanol were all separated using this approach. The alcoholic content of confiscated whiskey samples was assessed and compared to previously authorized samples with a 95 percent confidence level. The devised method has a fast analysis time which is less than 180 seconds, linear behavior in the range of 1.0 to 25% alcohol by volume with $R^2 = 0.98$, and a LOD of 0.5% ethanol by volume. The methodology described herein may be a straightforward and effective microchip strategy for quality control as well as a quick tool for determining the authenticity of whiskey samples. Such an inexpensive authenticity system may be valuable for the consumer.

In another study, Cordeiro et al. [105] presented a rapid, simple, yet reliable method for determining the ethanol content of various liquors depending on oxidation reaction with the use of a UV-LED/ H_2O_2 system as a solvent extraction step before to CE with the UV detector. In terms of ethanol, the LOD was 50 $\mu\text{mol/L}$. The proposed method was successfully applied to the analysis of 12 distinct

categories of alcoholic drinks with ethanol concentrations ranging from 5% v/v for beer to 53 percent v/v for scotch whiskey. Churski et al. [92] demonstrated a microfluidic platform for determining the concentration of ethanol in micro-droplets (Fig. 2C). In comparison to previous tests, the microdroplet approach delivers good reproducibility with a relative error less than five percent, high selectivity for ethanol, low reagent usage, and a wide range of 1–70 g/L. They demonstrated that the reliance of ethanol production on glucose content can be used to screen fermentation conditions and alcoholic beverage quality using high-throughput microfluidic technologies. The amount of sample required for each experiment can be greatly reduced by incorporating the well-known enzymatic assay for ethanol detection into the micro-droplet format. This enables high-throughput screening and extends the range of ethanol concentrations that can be detected. These benefits render the system appropriate for fermentation research in the industry for ethanol concentration at various production stages. For quality monitoring of single malt Scotch whisky, Ashok et al. [108] proposed using near infrared spectroscopy on a fiber-based optofluidic device. They showed that Raman spectra may be used to predict the alcohol level of a beverage to within one percent prediction error. In addition, principal component analysis (PCA) was used to classify whiskies depending on their age, kind, and cask. The findings indicate that this optofluidic probe is ideally suited for developing portable devices for alcoholic beverage authentication.

Sensors have an important role in determining the quality of drinks, particularly ethanol and other alcohols. For example, Da Silva et al. [106] have described a method for quick on-line ethanol content assessment using a terahertz sensor and a microfluidic platform. The absorption coefficient of liquid altered as permittivity varied due to varying ethanol concentration. The transmission signal from which they detected ethanol content rose or declined as a result

TABLE 2 Quantifying of ethanol using microfluidics.

DETECTION METHOD	LIMIT OF DETECTION	WORKING RANGE	REFERENCE
Micellar electrokinetic chromatography (MEKC) on microchips	0.5% (v/v) for ethanol	between 1.0 and 25% (v/v)	[103]
Photochemical oxidation under UV-LED irradiation	50 $\mu\text{mol/L}$ for ethanol	between 5% v/v to 53% v/v	[105]
Droplet microfluidics with enzymatic assay	70 g/L	1-70 g/L	[92]
Microfluidic devices and Gigahertz sensor	–	between 9.35% and 70.80% of ethanol	[106]
Microfluidic bioassay with hydrogel sensing elements	70 μM of alcohol	–	[107]

of this alteration. They identified equivalent quantities between 9.35% to 70.80% in a concept-proof for water-alcohol combinations. This device could be used in the drinks and chemical industries to perform in-line concentration measurement and control on small samples with a low error of 0.32 percent between measured and original concentration. Jang et al. [107] developed microfluidic devices with strips of hydrogel sensing microstructures that entrap quantum dot (QD)-enzyme conjugates for simultaneous glucose and alcohol detection. The model enzymes were glucose and alcohol oxidase, which were coupled to carboxyl ended CdSe/ZnS QDs and confined inside the hydrogel spherules, resulting in a fluorescent hydrogel grid that was glucose or alcohol-responsive. Based on the response, the quantity was determined. This systems' LOD were discovered to be 50 μM and 70 μM for glucose and alcohol, respectively. Because their innovative microfluidic system included many microchannels, they were able to detect glucose and alcohol simultaneously, and each micro-channel could run various assays independently, which could be useful for beverage quality monitoring.

Ethanol biosensors have recently played an important part in the quality determination of alcohols, where enzymatic processes are used to detect and quantify ethanol. Alcohol dehydrogenase, alcohol oxidase, and microbes are the three basic bio-components employed in biosensors [109-111]. Ethanol biosensors operate over a wide range of values with typically a linear correlation between ethanol concentration and measured signals. They have a low LOD of 0.1 μM and a fast detection time (seconds to minutes) [112].

Methanol concentration

While preserving the alcohol concentration, it is also critical to guarantee that the liquor contains no hazardous compounds. Methanol (methyl alcohol) is of particular significance since it can be toxic at high concentrations, causing blindness and even death [113,114]. The maximum concentration allowed by the US Food and Drug Administration and the European Union in distilled spirits is normally 0.35% to 0.5% (depending on the spirit) [113,115]. As a result, microfluidic technologies enable the development of cost-effective, portable devices for quick methanol detection.

In one study, Wang et al. [116] introduced a methanol detection microfluidic distillation chip that includes a serpentine channel. It also has boiling and heating zones, and the cooled product was collected in deionized water. The serpentine channel is used to transport the ethanol-methanol-water mix. Then, using a nitrogen carrier gas, it was collected in a chamber where it condensed in water. The combined indication and the methanol concentration

obtained by spectrophotometer absorbance measurements react with the condensate, which also contains nitrogen. It has a distillation efficiency of 97.9 percent and can detect methanol concentrations between 300 and 800 ppm.

Another paper describes the first time that electrochemical derivatization was combined with a hybrid CE platform [117,118] and capacitively coupled contactless conductivity detection to monitor methanol and ethanol concentrations during the distillation process to ensure the quality of the liquor [93] (Fig. 2D). This method can measure both methanol and ethanol simultaneously, with a LOD of 20 and 50 $\mu\text{mol/L}$ for ethanol and methanol, respectively. Based on Waveguide Confined Raman Spectroscopy, another analysis revealed an optofluidic sensor for predicting both the methanol concentration (toxicity) and the ethanol concentration (quality) with 0.1 and 0.7 percent accuracy by volume using a Partial Least Squares-based chemometric model [119]. This sensor was used to analyze two vodka samples and one whiskey sample, and the model was able to clearly distinguish harmful beverages. Each model has its portability, low power requirements, and small sample quantities. The suggested approaches can be used not only in the lab but also in the field and even as an in-line monitor for distilleries.

Drop drying

We can investigate the pattern creation left by drying droplets as a simple technique of identification and classification of beverages. The suspended micro- and nanoparticles in liquids form monolayers and/or are gradually deposited during the evaporation process resulting in the formation of diverse structures. Indeed, the formation of complicated systems from a droplet of colloidal suspension on a flat plane is a well-established phenomenon that has been utilized to describe blood serum, proteins, bacteria, DNA suspensions, and organic compounds, among other things [120-124]. Similar approaches can identify and analyze spirits.

Some studies were conducted based on drying droplet by evaporation to identify and classify drinks. For example, González-Gutiérrez et al. [125] reported an approach based on crystallization patterns formed during the evaporation of alcohol droplets. They discovered that adding salt to the drying process enhances the gathering of crystals around the colloids, but that there were no apparent patterns in pure samples as shown in Figure 3A. They found that tequila patterns are easily repeatable. They identified that when different sample droplets were dried, they form a different pattern of structures that can be distinguished by density profiles and concluded that the method can distinguish between pure and contaminated drinks. In another work, Carrithers et al. [126] revealed that when a drop of

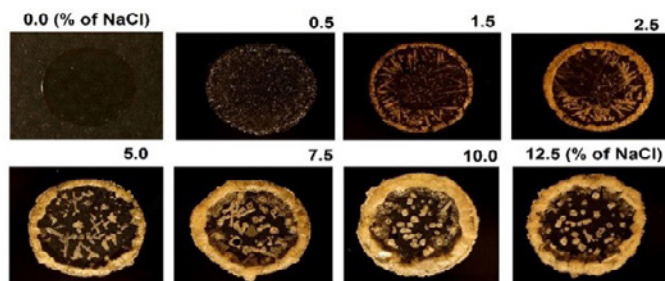
American whiskey was evaporated, a self-assembled pattern arose and deposited on a surface to form hierarchical weblike patterns that they dubbed it a "whiskey web" [127]. The resulting pattern can be utilized as a liquid's chemical fingerprint, which not only distinguishes each item but also explains the distinct pattern of deposits from drying droplets for each substance (Fig. 3B).

Yakhno et al. [128] recently proposed a novel method for deciding the similarity/difference between spirits without measuring their constituents, due to a high responsiveness of the oscillatory sensor's electrical behavior to the dynamics of a drop of the sample drying on the surface. Each liquid generates its own types of imprint, which is represented by the geometry of the amplitude curve or the difference index in the proximity of the hodographs (Fig. 3C). The scientists claim that despite the fact that droplets of drinks must evaporate under normal room settings, the dynamic "fingerprint" might replace the regularly used barcode and form a basis for wine product authentication.

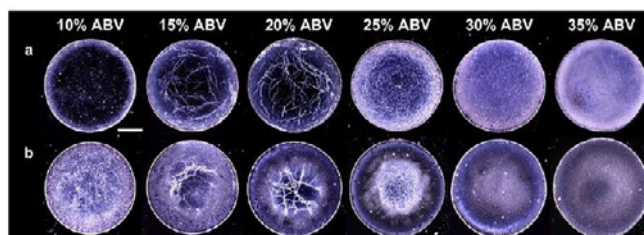
Volatile Organic Compounds (VOCs)

The chemical composition of alcoholic products is extremely complicated, with 300-1500 distinct chemicals found in various liquors [5,10,11]. Fermentation, aging, and storage produce aldehydes and ketones, which contribute significantly to the characteristic aroma of alcoholic beverages. Drinks have a diverse aroma because of these VOCs. Because it is predicted that adulterated and/or faked items will have a considerably different chemical composition than authentic samples, determining chemical indicators in alcoholic beverage samples can be used to investigate the process of certifying the drink's quality and authenticity [101,102].

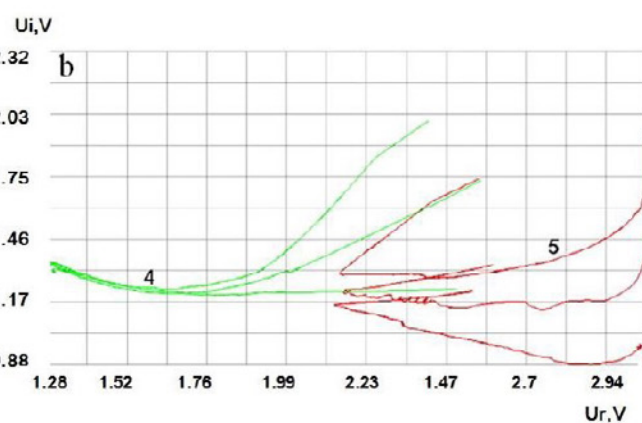
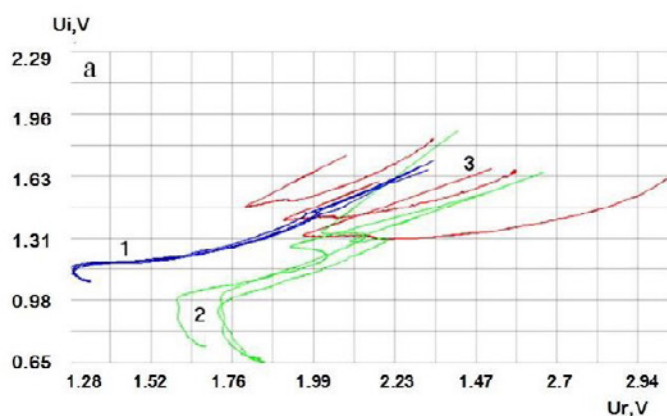
Studies that were previously discussed in the Maturation section can be applied to this section to identify different liquors. In addition, there are some studies in literature that can identify the drinks based on different VOCs. Heller et al. [129] used CE to establish a quick analytical method for determining the aromatic aldehydes namely, conifer-aldehyde, sinapaldehyde, vanillin, and syringaldehyde in



(A)



(B)



(C)

FIGURE 3 (A) The effect of diluting on the deposited whiskey patterns. The creation of webs in different ages of whiskey: (a) 3 years old, (b) 23 years old. Reprinted with permission under a Creative Commons Attribution-NonCommercial 4.0 International License from [126] (<https://doi.org/10.1103/APS.DFD.2018.GFM.P0002>) (B) Aggregation pattern observed in Tequila sample as a function of NaCl concentration. Reprinted with permission from [125] (Copyright 2017 AIP Publishing) (C) Hodographs of liquids of various types in a variety of shapes: Dry red wine is number 1; cognac is number 2; whiskey is number 3; balm is number 4; and vodka is number 5. Reprinted with permission under a Creative Commons Attribution-NonCommercial 4.0 International License from [128] (<https://doi.org/10.3390/s20185266>)

whiskey, as well as to monitor the concentration of these chemicals in real and seized samples suspected of being false. They investigated 32 different Scotch whiskey samples in the study, and they separated authentic samples from questionable ones in under a minute. The analysis of such chemicals in whisky samples can help learn more about the procedures involved in whiskey manufacturing as well as to ensure the quality and authenticity of the beverage.

In one study, a gas sensor made by metal oxide was incorporated into a digital microfluidic platform to identify VOCs in wine aromas via liquid sample analysis [130]. A hydrophobic porous microchannel mitigates the influence of the gas sensor's water cross-sensitivity, enabling the detection of wine aromas selectively. The transient responses of the device to diffused aromas from seven different wines, including three distinct types of shiraz, sauvignon blanc, cabernet, shiraz/cabernet blend, and syrah are recorded and compared along the channel in order to differentiate between different types of wine, as well as their producer and vintage years. To successfully apply the method, it is important to increase the selectivity range of the gas detector for different VOCs. The same author evaluated the effect of coating the channel and polarity of the analytes on the gas detection techniques of a microfluidic-based gas detector for this purpose [131]. When it comes to selecting the appropriate channel coating, the data indicate that non-polar coating surfaces exhibit more selectivity against non-polar gases, while polar gases are less affected. This can be utilized to create a set of micro-channels with different polarities to boost the device's separation power. Ghafarinia et al. [132] used microfluidic channels with a single

gas sensor to differentiate eight alcohol vapors, including their isomers, based on their differing rates of diffusion and physisorption, to boost selectivity.

Another way to accomplish the duties described is to use an electronic nose [133,134]. Zhang et al., for example, proposed the NOS.E, a new E-nose instrument with an auto-mated air intake design that was employed for standardization of odor detection and identification purposes [135]. Using the PCA pattern recognition technique, the sensor array can produce various VOC profiles that can classify and detect three different alcohol samples. It also includes a fault detection and alarming architecture, allowing it to deliver high-reliability results by constantly checking its operational state. While the proposed NOS.E (Sensitivity: 1ppm, Noise Level: 2–32mV) does not yet equal the capabilities of existing e-nose systems, it does provide end users with configurable odor evaluation platform that enables them to create their own sensor array. This and other similar microfluidic monitoring systems can rapidly detect if the spirit has been compromised and may aid in the identification of the source of contamination.

Based on the differential pulse voltammetry technique's selected current component, Wójcik et al. [136] employed voltametric sensors to profile wine and Scotch whisky samples with a complicated composition using voltametric sensors. This novel technique has the potential to represent a significant step forward in the development of voltametric complicated sample profiling, as well as the fabrication of electronic tongues. A multi-sensor fusion system was developed in another study, based on a revolutionary cost-effective E-nose and a voltametric electronic tongue.

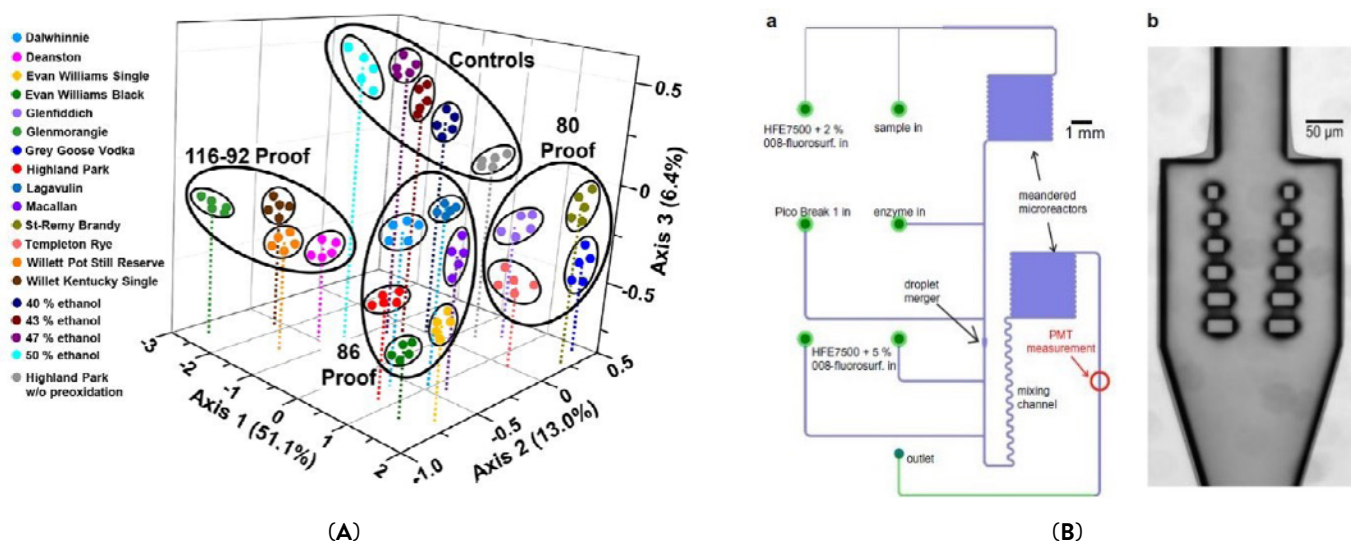


FIGURE 4 (A) Identification of different liquors based on the PCA score. Reprinted with permission from [139] (Copyright 2018 American Chemical Society) (B) (a) Schematic of microfluidic chip producing and merging droplets. (b) Close view of merging microdroplet cavity. Reprinted with permission under a Creative Commons Attribution-NonCommercial 4.0 International License from [140] (<https://doi.org/10.1007/s00216-018-1516-6>)

The system can successfully classify red wines with different brands, geographical origins, and grape varieties [137]. The results suggested that extreme learning machine models by PCA scores of E-noses and tongue as inputs have a strong potential for quick red wine quality evaluation. For more information about E-nose application, we would like to refer the reader to a review article by Sanaeifar et al. [138], where he discussed the application of E-noses in beverage analysis.

In a separate study, Li et al. [139] proposed a colorimetric sensor array for the rapid and easy identification of liquors such as rye, scotch, vodka, bourbon, and brandy that utilizes multiple classes of chemo-responsive sensor inks such as pH indicators, redox indicators, acid/base indicators, specific aldehyde/ketone sensitive indicators, and solvatochromic dyes. The sensor, which is based on hierarchical cluster properties, PCA, and SVM analysis, accurately categorizes 14 liquors by their alcohol by volume and brand name, with a rate of >99% accuracy (Fig. 4A). Additionally, the sensor array is capable of detecting dilution (i.e., "watering") of distilled spirits with a water input of as little as 1%, highlighting its potential for quality control and assurance in the spirits industry. This handheld device can be used as means of portable quality control assessment, including confirming appropriate dilution.

The colorimetric sensor systems arguably offer the greatest option for a low-cost, portable, yet sensitive way of assessing wine quality, especially given its capacity to account for large amounts of chemical information on the flavor constituents. However, because colorimetric sensor arrays use a visible spectrum of light (RGB, with wavelengths spanning from 0.4 to 0.75 μm), the extremely minute particles in wines scatter at their highest under the Mie scatter reign [141], deteriorating the performance of this sensor array. Because undiluted red wine runs over chromatographic paper, particulate matter is removed from the red wine, paper microfluidics can be used as an expendable and low-cost replacement to calorimetric sensor arrays. Park et al. [142] devised and built a system to assess ten distinct red wines and distinguish them from one another using a set of chemical dyes. The photos were taken with a smartphone's digital camera, and the red-green-blue color intensities were evaluated using PCA to differentiate each sample. The image processing and PCA approach might be turned into a standalone smartphone app for evaluating red wine and other beverage goods.

Other Approaches

In this section, we'll show research that doesn't fit into any of the previously mentioned categories. For example, Reid et al. [143] explored different methods for confirming food authenticity and quality, and they might be employed

in a microfluidic regime to identify and quantify specific components. Our discussion will be limited to the microfluidics regime, where other components, such as sulfite, sulfate, histamine, and others, have been found and quantified.

Rovio et al. [144] used capillary electrophoresis to identify organic acids, inorganic cations and anions, and carbohydrates, as well as spectrum analysis, which determine chemical distinctions between six red wine samples from various locales. The pinot noir grape was utilized as a common nominator, and sensory assessment was performed to identify distinctions between wines. To monitor inorganic anions, Freitas et al. [145] employed environmental samples Cl^- , NO_3^- , SO_4^{2-} , and NO_2^- electrophoretic separations were successful, with LODs ranging from 2.0 to 4.9 $\mu\text{mol/L}$. The proposed analytical methodology can be utilized for routine environmental analysis and may be useful for the analysis of various ions in spirit, based on the results presented here. Rezende et al. [146] compared the concentration of those ions to that of original samples to authenticate seized whisky samples. They used microchip electrophoresis (ME) devices with contactless conductivity detection that was capacitively connected. ME devices differ from other microcapillary electrophoresis devices in that they provide quick analysis, low sample consumption and waste generation, high-throughput analysis capability, and compatibility with additional analytical stages on a single platform makes them suitable to be used in the industry [147-149]. The proposed microfluidic technology, according to the data, might aid regulatory authorities in the investigation and monitoring of the validity of commercialized whiskey beverages.

Sulfite is commonly used as an antioxidant and antibacterial ingredient in beverages. On the other hand, it also has negative health effects in asthmatic patients, hence proper sulfite content assessment is critical to ensure the quality [150]. Vervoort et al. [140] created a reusable microdroplet technology (Fig. 4B) that can assess sulfite concentrations with a small sample of a fermented product with a LOD of 0.004 ppm and a three-orders-of-magnitude dynamic range. Although the tight array of micropillars prevents steady droplet reinjection, eliminating the pillars and combining miniaturized pumps and optics would allow this device to be used for high-throughput screening. While low levels of histamine in food are not regarded as a severe health danger, high doses can cause histamine poisoning [151]. As a result, determining the concentration in foods and beverages is an important consideration for maintaining quality. To overcome the issue, Stojanović et al. [152] suggested an electrochemical method for the voltametric measurement of histamine based on bulk-modified carbon paste electrodes with single-walled carbon nanotubes.

It was acceptable for determining histamine levels in industrial beer and wine specimens since it had a low LOD of 1.26 $\mu\text{mol/L}$ and a quantification limit of 3.78 $\mu\text{mol/L}$ of histamine, as well as good reproducibility. The findings indicate that the suggested differential pulse voltammetry technique offers a potentially useful analytical tool for routine quality control of alcoholic beverages with reference to their histamine level.

ADULTERATION/TOXIN DETERMINATION

Microfluidics analytical devices have already established themselves as a valuable tool as an alternative to traditional laboratory methods due to the ability for high-performance assessment in the food safety and quality industries. Biotoxins, foodborne pathogens, heavy metal ions, food allergies, and other chemicals present in food have all been determined using microfluidic devices [153-155]. However, the time-consuming sample preparation and detection techniques required by the varying complexity of a food matrix necessitates the incorporation of additional processing elements into the microfluidic chip, hence restricting the usefulness of microfluidics.

Different spectroscopy approaches can be used with microfluidics to facilitate on-site analysis for different pollutants detection in food and beverages. Surface-enhanced Raman spectroscopy (SERS) techniques, for example, are becoming more widely used and accessible for the accurate and precise identification of chemical and microbiological contaminants in foods. Pu et al. [156] studied these approaches and their integration with microfluidics, concluding that they have tremendous potential for quick food contamination analysis. Additionally, the use of spectroscopy techniques combined with chemometrics enables for the quick and non-destructive examination, characterization, and identification of whisky fraud [157]. Combining NIR, MIR, and Raman spectroscopy with microfluidics, for example, can detect phony whisky and kindred beverages. Additionally, E-noses have emerged as a viable tool in a variety of fields of food safety evaluation for the speedy early detection of pollution and defects in the food supply chain [138]. It is associated not only with aroma profile but also for various contamination detection such as spoilage, mycotoxin. Spectroscopy can also be used with an electronic nose to detect flaws in beer and other beverages, which can be beneficial to small, medium, and large breweries. Viejo et al. [158] demonstrated a complicated approach for detecting flaws in beer that warrants additional investigation.

Recently, various toxic components have sparked interest in screening in cases of alcohol adulteration. Urea, ochratoxin, scopolamine, and flunitrazepam are just a few examples. To guarantee that alcohol will be used safely, it is required to test potential contamination. Iida et al. [159]

devised a method for determining urea in rice wine by combining microfluidics and an acid urease column-flow injection analysis system device, and the system was used in rice wine to determine urea. The proposed FIA system can determine urea in the range of 16 μM to 1 mM. Because the suggested method is not affected by ethanol or ammonia in samples, it can be used to determine many different types of amino acid oxygenase, decarboxylases, and amino-acid oxidase. Novo et al. [160] created a microfluidic enzyme-linked immunosorbent test device for detecting ochratoxin A(OTA) in different solutions more importantly in extracts of beer and wine. The LOD in pure phosphate buffered saline was 0.85 ng/mL using a straight channel arrangement for OTA. Even though the model was not validated with real samples, the system represents an important step for the creation of devices for OTA monitoring in the wine and beer industries. Jornet-Martínez et al. [161] created a Scopolamine sensor based on the entrapment of the reagent KMnO_4 in PDMS, which is intended for quick Scopolamine analysis in beverages. The LOD is 108 $\mu\text{g/mL}$. A portable nano liquid chromatograph method was also developed, with a LOD of 100 $\mu\text{g/mL}$ in this case. The proposed methodologies were tested on a variety of alcoholic and non-alcoholic beverages, demonstrating the viability of the two approaches for on-site testing. Tseliou et al. [162] created low-cost, electrochemical cells printed on a lab-on-a-screen for the direct, cathodic voltammetric detection of flunitrazepam in a variety of alcoholic and soft drinks. The system is ideal for a wide range of acidity (pH 2.3–8.4) and alcohol concentration (up to 40% alcohol by volume). The sensor's good performance for point-of-need screening of flunitrazepam to prevent covert drug administration is demonstrated by the data.

SUMMARY AND PERSPECTIVE

To meet regulatory and consumer needs for spirits quality and safety control, the invention of cost-effective, portable, rapid, and extremely sensitive measuring instruments is necessary. Microfluidics devices continue to demonstrate their reliability and sensitivity to complement or replace established laboratory procedures due to their ability for high-performance assessment in the alcoholic beverages quality and safety sectors. In comparison to other disciplines such as clinical and environmental screening, contemporary microfluidics technologies for beverage analysis have been underused [155]. One challenge in its adoption is sample pretreatment, as it requires the integration of additional processing elements into the device, increasing the costs and complexity of the device. Specific testing aims may be efficiently achieved by utilizing physical properties to simplify sample preparation operations and by boosting

microfluidic transport via microfluidic electrokinetics, inertial focusing, and other approaches. As a result, increased attention should be directed toward developing a variety of microfluidic platforms for real-time liquid sample analysis that include an integrated pretreatment process. Additionally, the described microfluidics or associated platforms typically target a single analyte and/or are limited in their analysis. But it may be necessary to develop systems that can be used for multiple analytes simultaneously.

This review demonstrates the feasibility of in situ monitoring in the spirits business using a variety of approaches. A large number of integration opportunities for detection capabilities leads to more precise devices. The most frequently utilized chemical sensing methods include potentiometric, optical, chemical, and electrical detection [68,69,105,128]. Different sensing approaches in health sciences consequently increased the versatility of microfluidics in beverage analysis. For instance, a variety of detecting membranes are frequently utilized in beverage analysis [112]. Additionally, several electrokinetic separation techniques, like capillary electrophoresis, are the most adaptable for separating and quantifying chemicals in liquors and will continue to be used in microfluidic analytical systems. Recent advances in spectroscopic detection and machine learning have expanded the scope of this field [91,108]. Different machine learning algorithms can compare and predict different components at the same time using data from spectroscopic detections. This review demonstrated that the aforementioned methodologies have been successfully utilized to analyze various components — including ethanol [92], methanol [116], pH [73], and other VOCs [101] — in order to monitor the spirits' quality. Microfluidic technologies have also been used to identify some common contaminants or adulterations. Among these include urea, ochratoxin, scopolamine, and flunitrazepam. The findings indicate that several technologies have considerable potential for further research and commercialization in the spirits business.

Emerging areas like turbidity, stability, foaming, color, etc. could be integrated with microfluidics for quality control. It can monitor variations in foaming stability regarding different properties of the liquors. For example, microfluidics can also determine viscosity [163] and how it can vary depending on the content of various components [164]. Even though current microfluidics studies have not focused on spirits, underlying fundamental microfluidics concept can determine how liquid properties change with changes in ethanol, amino acids, polyphenols, and so on. We can thus analyze fluid composition by investigating changes in viscosity, which can positively or negatively affect surface tension at the interface, and hence foaming stability. The identification of color consistency is another

thing that microfluidics could be used for. For example, the optical properties of spirit droplets can be analyzed for refractive index and color inconsistency [165] and could be applied to assess turbidity.

In conclusion, this study discussed the significant advancements in microfluidics in the assessment of spirits over the recent years. The analysis and viewpoints presented in this study are believed to stimulate continued development of microfluidic devices in the spirits sector and other food safety testing and monitoring fields, benefiting human health and overall well-being.

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