beverages

MDPI

Review

Innovation and Development in Whisky Production Around the World

Victor L. Espitia-López [1], Frida P. Malpica-Sánchez [1], Héctor B. Escalona-Buendía [2] and José R. Verde-Calvo [1,*]

[1] Enology and Fermented Foods Laboratory, Biotechnology Department, Universidad Autónoma Metropolitana–Iztapalapa, Av. Ferrocarril San Rafael Atlixco No. 186, Mexico City 09310, Mexico; vlel@xanum.uam.mx (V.L.E.-L.); malbec@xanum.uam.mx (F.P.M.-S.)

[2] Sensory Analysis and Consumer Laboratory, Biotechnology Department, Universidad Autónoma Metropolitana–Iztapalapa, Av. Ferrocarril San Rafael Atlixco No. 186, Mexico City 09310, Mexico; hbeb@xanum.uam.mx

* Correspondence: jrvc@xanum.uam.mx

Abstract: Whisky is one of the leading distilled spirits and is produced in multiple countries under the regulatory standards of its country of origin. The spirit is usually produced from barley malt that may have other cereals present and produces a fermentable substrate by the addition of yeast. This substrate is then distilled in pot stills or distilling columns and matured in oak casks. The standard production workflows applied, and cereals utilised in the primary production regions, have been studied to aid understanding of the production process. Moreover, novel alternative grains and production means have been investigated, highlighting the spirits versatility. This review aims to present an in-depth summary of the complete production process from the selection of raw materials, the various production processes from across the globe, and an introduction to some of the newer more innovative methodologies utilised to produce whisky today.

Keywords: whisky; whisky production; malt; mashing process; fermentation; distillation; maturation

check for updates

Citation: Espitia-López, V.L.; Malpica-Sánchez, F.P.; Escalona-Buendía, H.B.; Verde-Calvo, J.R. Innovation and Development in Whisky Production Around the World. *Beverages* **2024**, *10*, 124. https://doi.org/10.3390/beverages10040124

Academic Editor: Antonio Alfonzo

Received: 24 October 2024
Revised: 14 December 2024
Accepted: 18 December 2024
Published: 20 December 2024

1. Introduction

"Whisky", written as such by the Scots, and "whiskey", written by the Irish and Americans, is a grain-based alcoholic beverage, fermented, distilled, and matured, usually in oak [1]. This spirit offers a wide range of sensory experiences that are appreciated by both casual and connoisseur consumers [2]. Raw materials used for its production and the variation in the production process are subject to the laws and regulations of where it is produced. Among the top whisky and whiskey-producing countries are Scotland, Ireland, the United States, Canada, and Japan [3], followed by others such as Thailand, France, China, and India [4,5].

Scotland generates the most exported and recognised whisky brands worldwide with five types of whisky: single-malt Scotch whisky, single-grain Scotch whisky, blended-malt Scotch whisky, blended-grain Scotch whisky, and blended Scotch whisky [6], followed by other whisky-producing countries that must comply with the corresponding regulatory standards. Some of the characteristics are shown in Table 1.

New whisky-producing countries, excluding internationally recognised producing countries, include some distilleries located in Spain, whisky operations in Turkey, breweries where whisky distilling has been implemented in Pakistan, whiskies that have developed a style identity in Sweden, and significant distillery expansions in Australia. Looking at the craft whisky phenomenon worldwide, with a more minor but no less critical level of production, one can find Switzerland, Austria, Argentina, Belgium, Brazil, the Czech Republic, Denmark, England, Israel, Italy, Liechtenstein, Finland, Germany, Iceland, the

Netherlands, New Zealand, Norway, Russia, South Africa, and, with a high probability, many more countries [7].

Table 1. Regulations and characteristics of top whisky-producing countries.

Country	Characteristics
Scotland	Scotch whisky must be distilled in a distillery from water and malted barley, to which only whole grains of other cereals may be added and which has been processed in that distillery by mashing, converted into fermentable substrate only by endogenous enzyme systems, and fermented only by the addition of yeast. This whisky must be distilled to an alcoholic strength of less than 94.8% and aged for a minimum of 3 years in Scotland in oak casks, each with a maximum capacity of 700 L. The only ingredients that must be added to it are water and plain caramel colouring, with a minimum alcohol content by volume of 40% [8].
Ireland	According to the definition of Irish whiskey, the spirit must originate from a cereal mash that has been converted into sugar by malt diastase and possibly other natural diastases, undergo fermentation through yeast action, be distilled at an alcoholic strength below 94.8% volume, and be aged in wooden casks for a minimum period of 3 years [9].
United States	A 51% minimum blend of corn, rye, wheat, malted barley, and malted rye is required for the production of bourbon whisky, rye whisky, wheat whisky, malt whisky, and rye malt whisky, respectively. Bottled at 160° proof and aged at a maximum of 125° proof in new charred oak barrels. Corn whisky must be produced from wort that contains at least 80% corn [10].
Canada	Canadian whisky must be made from a mixture of cereal grains or cereal grain derivatives that are converted into fermentable sugars by malt diastase or other enzymes, fermented with yeast or a combination of yeast and other micro-organisms, aged in small casks for at least 3 years, containing a minimum of 40% alcohol by volume, and may also include caramel and flavourings [11].
Japan	Japanese whisky is defined as being produced from malted grains, other cereal grains, and water sourced from Japan. The alcohol content at the distillation process must be below 95%. The spirit must be aged in wooden barrels with a maximum capacity of 700 L for a minimum of 3 years. Bottling can only take place in Japan, with a minimum alcohol content of 40% and plain caramel colouring permitted [12].
France	For whisky Bretagne and whisky d'Alsace, France is the country of origin. Whisky Bretagne Federation mentions that barley malt, wheat, buckwheat, corn, or rye may be used for this type of whisky to be recognised in the production process [13].
Thailand	Thai whisky can be used in barley malt, molasses, and rice [4].
India	For Indian whisky, barley malt, molasses, and grains such as corn, rice, sorghum, and millet can be used [4].
China	Chinese whisky is made from barley malt and cereals such as rye, wheat, corn, barley, or oats [14].
Mexico	Mexican whisky uses raw materials such as barley, rye, wheat, and corn. Corn whisky has the possibility of not requiring ageing in its production process [15,16].

To limit the use in the variation of names "whisky" and "whiskey", the word "whisky" will be used when referring to this distilled beverage during the rest of the review, considering the exceptions when the origin or place of production is specified. Figure 1 provides an overview of the whisky production process and the development and innovation variations arising from this review.

This review focuses on the differences in the processes of the top whisky-producing countries and the development in some other countries that, over time and in recent years, have increased their production and are beginning to have a substantial presence. The regulatory standards, the raw materials used as malts or adjuncts, and the process described in the mashing, fermentation, distillation, and maturation stages are presented. In each corresponding section, research on the innovation of this distilled beverage in different parts of the world is described. The references used are limited to research over time where new raw materials and alternatives have been used in the whisky production process, using the regulatory standards of the respective countries.

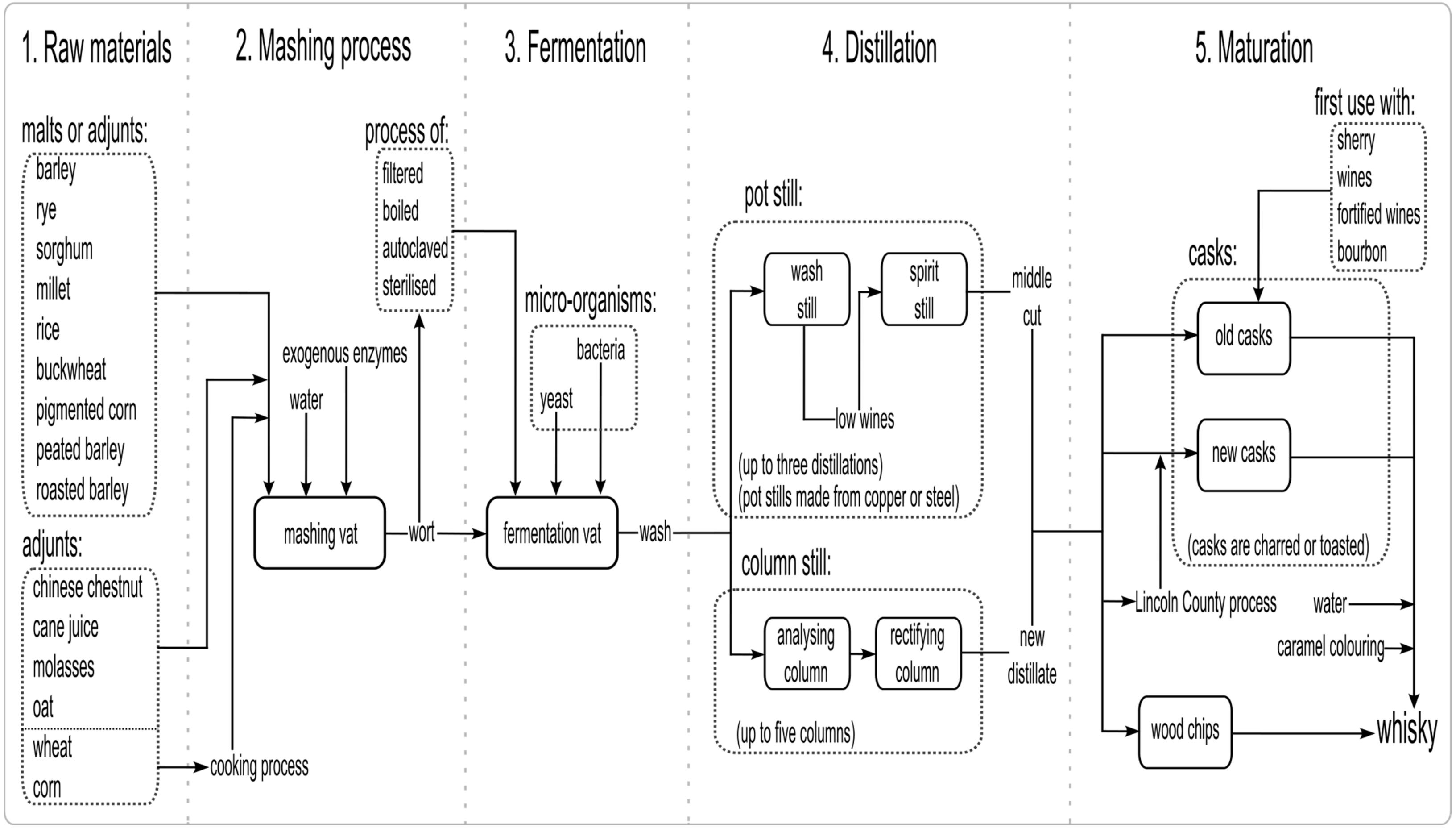

Figure 1. A process flowchart for whisky production. It is based on standard procedures and the innovative applications of raw materials, including both malted and non-malted ingredients, and variations in the techniques employed during mashing, fermentation, distillation, and maturation in this review.

2. Raw Materials and Malts

Barley (*Hordeum polystichum*), corn (*Zea mays*), rye (*Secale montanum*), and wheat (*Triticum vulgare*) are the grains most commonly used in the production of whisky, due to their main approximate total starch composition of (63–65)%, 72%, 68%, and 69%, respectively. Among these grains, barley is mainly used as malt due to the quality of its enzymatic content and its starch content compared to other grains [17].

Master distillers have thanked researchers for their findings, which have significantly impacted malt production, fermentation, and distillation. This improvement is attributed to comprehensive studies on barley and barley malt, initially providing insight into the characteristics that determine barley quality and yield and subsequently uncovering the intricacies of the fermentation process, including biochemistry and enzymology [18]. However, different literature reviews describe the research conducted over time on barley malt processing in the production of whisky distillation [19,20].

Malt whisky is mainly distilled in Scotland, with its flavour diversity often closely linked to the regions of Highland, Speyside, Lowland, and Islay [21]. Fermentation sugars are produced by enzymatic activity within the starch of malted barley employed in malt whisky. Conversely, grain whisky is made from a combination of several unmalted grains and a smaller portion of barley malt, derived from high-enzyme varieties to break down the starch in the grains. Historically, corn was the primary secondary grain used due to its slightly higher alcohol yield than wheat and barley, but it was eventually superseded by wheat for economic considerations [22]. Several studies have been conducted on these four grains used in whiskies around the world. However, the way these grains are used has evolved in response to the amount of whisky produced and consumed globally.

Swanston [22] conducted a study in Scotland that involved analysing protein levels and alcohol yield in spirits derived from various wheat varieties and their blends in order to identify the most commercially viable and suitable option for distillation in the context of substituting wheat for corn in grain Scotch whisky production. Research on the attributes of wheat, corn, sorghum, and millet had already been conducted, demonstrating favourable prospects for distillation from these grains at comparable nitrogen levels and offering long-term substitutes if wheat experienced economic fluctuations, as well as the processing of these grains in other regions [23].

Once these grains began to be studied from a yield perspective for use as adjuncts, studies were conducted on malting, followed by mash evaluations and studies on grain physiology to contrast these new malts with the barley malt already mentioned in previous studies.

Sorghum had an essential application in the brewing industry as opposed to millet, so they sought to provide information about the potential of millet as malt for brewing beer, alcoholic beverages, and other gluten-free products. In one study, these two grains were malted at 20 °C, 25 °C, and 30 °C and showed similar values for reducing sugars and free-amino nitrogen. The two grains malted at different temperatures showed a wide presence of sugars and amino acids required by the yeast during fermentation. These results correspond to important quality parameters since temperature variations during malting are challenging to control, and even if grains are processed in different countries, they will not harm the resulting malts [24].

The potential of malting grains studies like rice and buckwheat under various temperature conditions and time has shown that these malts exhibit patterns in reducing sugars, free-amino nitrogen, and a wide range of sugars and amino acids during the mashing of both malted grains. Rice malt yields more maltose than glucose, while buckwheat malt yields more glucose than maltose [25].

In addition, the physiology of barley malt has begun to be compared with that of new malts such as sorghum and millet. Reports provide that the optimal development during malting of these three grains and a proper mashing process is related to the soluble nitrogen, diastatic power, and amino acids present. These grains have the range of amino acids needed by the yeast for fermentation, diastatic powers of 34 °L in millet, 32 °L in sorghum and 46 °L in barley, and soluble nitrogen of 1.01%, 0.45%, and 0.65%, respectively [26].

Pigmented corn, such as red and blue corn, can convert their starch into fermentable substrates for beer production. These malted grains have diastatic powers of 39 °L for blue corn malts and 42 °L for red corn malts [27]. Red corn malts have been used in whisky production without adding adjuncts or barley malt, and with the particularity of a natural colouration from the anthocyanins in the raw material used [28].

A common practice that can be found in the Scotch whisky industry is smoking with peat smoke during the drying stage of barley malt, which provides the final product with smoky and medicinal aromas [29]. Japanese whisky industry takes the knowledge and technology in malts of Scotch whisky production [30]. Research has also been undertaken regarding the roasting of malts, a process already employed in brewing. The application of roasted malts in varying percentages for whisky production enhances the concentration of pyrazines and furans, significantly influencing the volatile aroma profile compared to a distillate derived from unroasted malt [31]. Sources of combustible material like spent coffee grounds have also been evaluated as a replacement for peat in the smoking of Scotch whisky malts [32,33].

A milling process must process the raw materials, malts, or cereals used to reduce their particle size. However, important aspects such as the turbidity generated in the wort by milling can have an impact on the development of esters during fermentation [34].

Currently, grains that were once used as adjuncts are being studied as malted grains. Different regional raw materials with great potential to produce whisky are being used, which is easily accessible for each country where this spirit is being produced.

A notable example can be seen in a study conducted in China, where baiju, a similar spirit to whisky, is produced [35]. Whisky production utilises Chinese chestnuts as the primary ingredient, and it utilises malt and rice in lesser quantities. The Chinese chestnut is one of China's most essential nuts, and it is a member of the family *Fagaceae* and the genus *Castanea Miller* [36]. The Chinese chestnut comprises macronutrients such as starch, proteins, and fats, as well as some mineral micronutrients such as phosphorus, calcium, iron, and vitamins [37].

In Brazil, the development of a beverage distilled from barley malt, as in malt whisky, and sugar cane, as in cachaça, has been studied. Different percentages of the worts of these raw materials combine to allow for fermentation and distillation, as is typically done in Scotch whisky. The distillate containing 50% of each raw material provides a better sensory result, obtaining a less astringent, acidic, and bitter profile in taste and mostly sweet and woody in aroma compared to the distillates made with 100% cane juice and 100% barley malt [38].

3. Mashing Process

The mashing process usually explained in whisky production is from barley, where the wort is made by breaking down the starch with the help of enzymes such as α- and β-amylases generated in the malting process since these worts made from milled barley malt can be mashed directly because of their high amylase activity. In contrast, worts produced from other unmalted cereals require the addition of barley malt as a source of enzymes. The malting process also generates β-glucanase enzymes that facilitate the breakdown of endosperm cell walls and release proteases and starch, breaking down some grain proteins into peptides and amino acids. These amino acids are an essential nitrogen source for yeast growth during fermentation [39]. Food-grade enzymes can also be added, or even green malt without the kilning process can be used as a source of enzymes [1], though this will depend on and be subject to the type of whisky and the country where it is produced.

There are different mashing processes, among which a batch process stands out, similar to the infusion process used in the beer industry, which consists of mixing the ground malt with water at a temperature of (63–68) °C for (0.5–1.5) h. However, in the grain whisky industry, a first cooking step is required for starch gelatinisation of cereals other than barley malt; this can be conducted as a batch process at a temperature of 120 °C for 1.5 h or by a continuous process, as is usually conducted in North America. Then it cools to around (60–65) °C, and the barley malt is added. In addition, the wort is usually filtered before fermentation, although in some processes, a higher yield is obtained by fermenting the unfiltered wort [39].

Unlike mashes made in beer production, it is not expected to boil the wort in whisky at the end of the mashing process [1]. This step has a destructive action on the microorganisms that may be present in the wort and destroys all the enzymatic activity activated during the malting and mashing process [40].

Maceration has been focused over the years on producing worts rich in fermentable sugars, available for yeast use during fermentation, and achieving high alcohol percentages. Researchers have employed multiple approaches to achieve this objective, such as combining grains and malts, examining the behavioural characteristics of dextrins within the wort, and running experiments with exogenous enzymes alongside other methods, all whilst adhering to the respective national regulatory requirements pertinent to the whisky's country of origin.

Studies demonstrate improvements during mashing where barley malt-based worts were made without autoclaved after mashing, which is then fermented under the same temperature conditions and yeast inoculum. Results show a lower specific gravity during and at the end of fermentation in the unsterilised wort, suggesting a higher conversion of sugars into ethanol compared to a previously autoclaved wort and a higher ethanol content. Fermentation of simple sugars such as glucose, fructose, sucrose, and maltose is similar for both worts. For dextrins of higher molecular weight than maltotriose, such as maltotetraose, maltopentose, meltohexaose, and larger dextrins, they are not processed in the sterilised worts but did change in the unsterilised wort during fermentation [40].

Another study that observes changes obtained in low wines by experimentation with worts is that of Daute [41]. Three barley malt worts were autoclaved, boiled, and filtered, then they were fermented and distilled on one occasion, demonstrating that no significant difference can be detected in the aroma of the low wines. While the sterilised and boiled worts have higher levels of esters and higher alcohols, the filtered wort treatment obtains lower congeners and a lower alcohol yield. It should be mentioned that the control wort, to which no treatment was applied, obtained a better alcohol yield and a lower specific gravity after fermentation.

In Nigeria, where sorghum is mainly used, the effect of individual and combined commercial enzymes such as α-amylase, β-glucanase, xylanases, proteases, and amyloglucosidases has been studied in mashes made by infusion based on Nigerian yellow sorghum malt. Results show that at 65 °C mashes, the α-amylase and β-glucanase enzymes contribute to obtaining a higher extract yield compared to 85 °C macerations, where similar extract yields are obtained with or without enzymes. This highlights that from infusion macerations at lower temperatures, processing costs are reduced by using enzymes in combination, and energy costs are also reduced since, while processing at higher temperatures, energy consumption may be higher. However, it is not necessary to use commercial enzymes, whose cost should be considered [42].

Some tests conducted in the United States on bourbons and rye whiskeys made according to the regulatory standard of this country were studied by employing a descriptive sensory analysis to denote their main characteristics based on the different blends of corn and rye grains used during the mashes, as well as in their maturation. The results highlighted significant variations in some descriptors of the sensory profiles obtained, such as apple, vanilla, and red wine aromas for a bourbon made with 70% corn, 20% rye, and 10% barley malt, while for a rye whiskey made with 70% rye, 20% corn, and 10% barley malt, the aromas that highlighted significant variations were hay/herbal, vegetables, and yeast [43].

4. Fermentation

Fermentation in the whisky industry is a stage similar to that of other alcoholic beverages, where, in most regulations, yeast is mentioned as being responsible for the process. However, a wide variety of organisms, such as other yeasts or bacteria, can be found in the malt or other cereals used to obtain the wort. In some specific cases in the production of Scotch malt whisky, brewer's yeast is used as it can result in a more desirable distillate flavour [17].

A wort used for making Scotch malt whisky industry typically has a specific gravity of 1060 to 1070, obtaining around 7.5% abv during fermentation, while a wort for grain whisky production has a specific gravity of around 1080 [44]. The yeast chosen for whisky fermentations can significantly influence the flavour of the whisky, so the yeast strain used is of great importance [45]. Yeast also produces a range of compounds, including acids, esters, aldehydes, ketones, other alcohols, and sulphur-containing compounds, which significantly contribute to the sensory character. The specific yeast strain used in fermentation can have a considerable effect on the spirit's flavour profile, largely due to the varying secondary metabolites produced by different yeasts, and this is particularly notable when aiming for a high alcohol yield [29].

In small-scale whisky production, wooden fermentation tanks are sealed, unheated containers are devoid of temperature regulation, and the carbon dioxide produced is released. In contrast, larger-scale production facilities, including grain whisky distilleries, utilise stainless-steel fermentation vats equipped with temperature controls and, occasionally, carbon dioxide collection systems. The fermentation process lasts between 40 and 48 h; shorter fermentations can reduce the quality of the alcohol produced, while overly long fermentations can result in bacterial development, which can cause ethanol loss and flavour defects in the finished product. Some of the bacteria found have been *Lactobacillus*, *Leuconostoc,* and *Pedicoccus* [17].

The *Saccharomyces cerevisiae* strain used in the fermentation of whisky is of great importance, not only in ethanol yield but also in the production of metabolites that contribute to the generation and presence of the flavour found in this distilled beverage. Distillers in the Scotch whisky industry are looking to solve sustainability issues such as water and energy reduction by selecting more efficient distillers' yeasts that work in conditions such as high-gravity wort fermentations [46]. Today, distillers can make decisions for optimisation, quality, and production using a variety of yeast formats such as dried, compressed, liquid, and stabilised liquid [47].

Specific strains have been developed for whisky production and hybrids have emerged, not only from the *Saccharomyces cerevisiae* beer strain but also from wild yeasts such as *Saccharomyces diastaticus* that are capable of producing a spectrum of enzymes that hydrolyse starch into fermentable sugars [1]. In addition, strains used in other industries, such as bioethanol, are implemented. *Saccharomyces cerevisiae* yeast strains used in alcohol fuel distilleries in Brazil were evaluated and compared with commercial yeast for Scotch whisky distillation, showing favourable results since one of these strains achieved a comparable yield and superior tolerance to stress during fermentation. The spirits from this strain had acceptable flavour profiles with sensory characteristics similar to newly distilled Scotch whisky [48].

A distiller's yeast must have essential characteristics: ethanol production, osmotic pressure, sugar tolerance, pH tolerance, temperature tolerance, good flocculation characteristics, good storage viability before use, fermentation rate, and proper metabolite generation. Scotch whisky distilleries and some others do not recycle the yeast as is done in breweries, nor do they allow the addition of nutrients that help the yeast or enzymes in the wort. Therefore, selecting the yeast strain is vital to achieving an excellent final ethanol yield [44].

Regarding specific studies on some types of whisky, there is research on Scotch whisky in which contamination with *lactobacillus* was evaluated, showing the harmful effect of contamination by reducing the final pH, increasing the specific gravity, and reducing the concentration of alcohol in the fermented wort, as well as the increase in the concentration of lactic acid and the alteration in the concentration of other organic acids. Some of these effects are attributed to the type of strain and size of the bacterial population, considering that the master distiller can create a mixed fermentation with the yeast and bacteria that generates the desired profile without sacrificing the ethanol yield during fermentation [49].

Lactic acid bacteria can vary during fermentation in the wort from raw materials such as malt or yeast [50]. Other bacteria that have been identified in fermentation samples from a Scotch malt whisky distillery in the Speyside region were *Lactobacillus fermentum*, *Weisella confusa,* and strains of *Weissella kimchii* [51]. It emphasises that bacterial growth can lead to the formation of lactic acid, acetic acid, and other metabolites that can affect the flavour of the final distillate [52].

Experiments have been conducted in which the addition of bacteria at the beginning of fermentation is intentional. However, in the production of Scotch whisky, this practice is not allowed. In some other countries such as Canada, India, Japan, or the United States, this restriction is not applied [53]. In Greece, where the influence of the addition of lactic acid bacteria employing Greek yoghurt to mashes made from barley malt and mashes made from rye grains was studied, barley malt and exogenous enzymes through ordinary fermentation in whisky with yeast and non-ordinary fermentation, with the addition of this type of lactic acid bacteria, showed the production of butanoic acid, ethyl butanoate, ethyl isobutanoate, and 2-phenylethyl butanoate, compounds that are not typically found in whisky. In addition, these yoghurt-treated whiskies had a higher ester and alcohol composition, contributing positively to the flavour after a 6-month maturation period [54].

Genetic improvement has also been studied in distillers' yeast used in whisky. A study reports the improvement of *Saccharomyces cerevisiae* strains by transformation with integration plasmids containing the α-amylase genes *LKA1* and *LKA2* from the starch-degrading yeast *Lipomyces kononenkoae*. The results demonstrate that the expression of the genes could directly convert a significant amount of starch to ethanol [55]. Other essential contributions report the investigation of the proteome in the alterations of protein levels occurring throughout the fermentation of yeast used in a grain whisky distillery, demonstrating significantly increased levels in a variety of proteins involved in protection against stress and nitrogen limitation [56]. The use of commercial yeasts for the availability and utilisation of additional nitrogen through peptides has also been reported to improve fermentation yields [57].

Report studies with different yeast species evaluated individually show a profile with greater efficiency in ethanol production for a *Saccharomyces cerevisiae* strain. Better production of volatile compounds and sensory characteristics for a *Wickerhamomyces anomalous* strain implementing a mixed inoculum system with the two different strains achieve excellent fermentation and potential for the elaboration of whisky with a favourable profile, providing an experimental scheme in the evaluation of micro-organisms that are not typically used in the industry of this distilled beverage [36].

5. Distillation

Whisky production employs two distinct distillation methods. Initial distillations typically involve a batch process using pot stills, resulting in highly flavoured distillates from two or even three distillation stages. In contrast, continuous distillation in columns produces slightly flavoured distillates, often used as a base for blended whiskies [17].

The distillation process in the industry varies according to the whisky and the country of origin where it is distilled. Scotch malt whisky is traditionally distilled in two pot stills, first in the wash still and then in the spirit still. In the United States and Canada, copper pot stills can also be used, while Irish whiskey is triple distilled. On the other hand, Scotch grain whisky is produced in distillation columns, or Coffey stills, developed in 1830 by Aeneas Coffey, consisting of two columns: the analysing column or beer column, and the rectifying column. However, distillation processes with up to five columns are used in the

United States. The heat source in the distillation process that is mainly used today is steam. However, pot stills are also used where solid fuels or gas are employed [39].

The main difference between the equipment used is the degree of rectification or alcohol concentration that can be achieved. In pot stills or batch distillation, low wines are achieved at around 23% abv in the first distillation from a wort fermented with 9% abv. Therefore, to achieve a higher alcohol concentration, a second or even a third distillation is necessary compared to continuous distillers, which are more efficient in obtaining around 94% abv during their operation [29].

The first distillation conducted in batches or pot stills starts with incorporating fermented mash into the wash still. The operation continues with heating, which stops when 1% abv is obtained. The second distillation is divided into three fractions: foreshots, middle cut, and feints; this process can last between (5–8) hours. The foreshots are what is obtained first. In most cases, they are not collected for use in the distillate as they contain a higher proportion of volatile and aromatic compounds such as ethyl acetate. This fraction corresponds to around the first 30 min when distillate is between (85–75)% abv. The middle cut, new distillate, or new make spirit is obtained when the alcohol concentration drops from (72–60)% abv, having a collection time of about 3 h, depending on the point of the cut to fractionate the final part of the feints [58]. By-products of the first distillation process include pot ale, which consists mainly of water, barley residues, yeast, soluble carbohydrates, polyphenols, copper, and proteins. The stills produced during the second distillation are composed mainly of water, copper, and low levels of acids and alcohols [59].

The batch distillation process affects the flavour of the whisky due to cuts made during distillation, as aldehydes and short-chain esters are predominantly found in the foreshots and new distillate fractions, whereas fuel alcohols and acids are located between the new distillate and feint fractions. Key design elements that influence the physical separation of compounds in pot stills include the pot still's height, the dimensions and orientation of the lyne arm, and the type of condenser employed. The master distiller's design, efficacy, and operational procedures dictate the concentration of congeners in distillation columns, and these compounds can still be present at low levels even when the distillate contains a high concentration of alcohol [60]. It has also been reported that the fermented wort can provide sufficient information on chemical compounds and sensory that can make up a new make spirit, saving time and allowing for greater experimentation of factors in the development of new recipes for whisky production [61].

Copper helps catalyse some reactions, such as forming sulphur compounds from sulphur-containing amino acids, the decomposition of unsaturated fatty acids into carbonyl compounds, and the dehydration of β-hydroxypropionaldehyde into acrolein [60]. Other compounds that can be formed during distillation are esters from alcohols and carboxylic acids. This occurs under low pH conditions and with the presence of copper ions contributing to the esterification process. However, ester formation is less significant in distillation than during fermentation [62]. Some aromas, such as vegetable, rotten egg, and rubber, tend to be reduced by these sulphur-containing reactions. That is why pot stills are usually made of copper, or some parts of them contain copper [29].

The whisky production regulations around the world do not impose the type of materials with which the pot stills wort are made for the distillation of this spirit. Some only mention a % abv, which must be respected during distillation. Because of this, studies on improving this process may be limited, except for some studies whose findings are based on assessing the performance of copper in various pot still sections and monitoring chemicals that may be impacted throughout the distillation process.

A study that evaluated the impact of the presence of copper in different parts of the composition in a wash still and a distillate pot still at the laboratory level in a double distillation for malt whisky production confirmed the reduction of sulphur-containing compounds and sulphur aromas in the distillate obtained, such as dimethyl trisulfide (DMTS). Copper used in the condenser of the wash still and in the boiler of the spirit still was found to reduce the levels of DMTS [63]. The perception of DMTS in grain whisky is rubbery, sour, and gassy, concerning the Scotch whisky flavour wheel [64].

Software is now available to characterise the behaviour of congeners during batch distillation. Such tools can provide useful information for master distillers to choose a form of distillation based on simulation data [65].

6. Maturation

Most whiskies produced worldwide are matured in American white oak casks initially made for bourbon maturation. They are generally made from *Quercus alba* species, with Kentucky and Missouri in the United States being the main cask-making areas. Wood may come from some other central or eastern states. After their first use, the casks are sold to whisky distilleries worldwide, such as Scotland and producers of sherry in Spain. For whisky maturation, there is also the manufacture of casks with oak grown in Spain from *Quercus robur* and *Quercus petraea* species that in first use are used to produce sherry, and some other oak casks from France and Portugal that are used in wines or fortified wines and are subsequently used for second maturation periods or whisky finishes. Japanese oak of the *Quercus mongolica* species is used in smaller quantities to manufacture casks, which are seasoned primarily with oloroso sherry wine, used in Japanese whisky distilleries [66].

The casks are not sealed tightly. Any compounds with a boiling point lower than ethanol will evaporate. Conversely, compounds with higher boiling points than ethanol will stay in the casks and could become more concentrated as ethanol evaporates. The maturation process greatly influences the final whisky, as the number of detectable compounds grows from hundreds in new distillate to thousands in aged whisky, although only a few wood-derived compounds directly affect the final flavour [62].

The main attributes of the taste characteristics of whisky are sweet, bitter, and sour. The sweet flavours come from sugars entering the spirit if a cask was previously used with wine, containing low levels of residual sugars such as fructose and glucose, while the bitter flavours are due to the presence of tannins extracted from the wood [67]. However, the use of newly charred casks is also associated with an increase in sugars such as arabinose, glucose, and xylose, as well as an increase in colour [39]. However, it is reported that the impact of volatile compounds is more influenced by oak origin and toasting factors than by charring [68].

Ethanol has been proven to be crucial in the kinetics of wood component extraction. The primary transformation occurring during cask maturation, especially in a new oak cask, is an increase in the distillate's colour, which transitions to yellow and deepens into a darker hue incorporating brown and red undertones that become more pronounced with time. The colouring agents are high-absorbance polymerised phenols with a low light index, which combine to produce the darker yellow/brown hue found in long-aged spirits [69]. The levels of volatile phenols are affected by barreling proof, level of toasting or charred, wood type, conditions of the barrel room, and how long the whisky is exposed [70]. In addition, inspection and measurement of cask volumes can help to detect contamination problems or leaks that may damage the whisky [71].

Of compounds derived from lignin, vanillin contributes to the flavour of Scotch whisky with the vanilla aroma; this compound is found naturally in wood in free or glycosidically bound form, while heat treatment during the manufacture of casks considerably increases the level of vanillin by thermal degradation of the lignin. Eugenol, guaiacol, and ethyl guaiacol, which are wood-derived compounds, are also formed by the thermal degradation of lignin and provide spicy aromas. Oak lactone, also known as 3-methyl-4-octanolide in its cis and trans isomers, is another significant aromatic compound that can be found in free form and glycosidically bonded forms. These isomers have a coconut-like aroma, and the levels that the spirit can extract depend on the content of this compound in the wood before heat treatment. For example, the American oak species used to age Scotch whisky has a higher level of cis isomer.

In contrast, European oak has an equal distribution of isomers, and Japanese oak has a higher level of trans isomers. The relative levels between the two isomers also vary depending on the oak species and the forest region [62]. In addition, some floral and mint notes that may be associated mostly with raw materials in the fermentation or distillation process may now be associated with maturation [72].

Matured whisky variation comes from cooperage practices, biological sources, and factors such as oak genetics that are uncontrol. Some parts of the cask production process lend themselves to research, including wood polymer decomposition, conditions that affect microbial communities, thermal events, and analysis of wood taints and flaws [73].

The maturation process is regulated under the regulations of each country where the whisky is produced with changes in the type of wood, the % abv at the beginning of the ageing process, the minimum time required, the maximum volume of casks used, and more factors depending on the place of production. However, some studies report differences in the variations of these factors and the application of other types of maturation.

Some reports compare the maturation of a Scottish malt distillate matured in standard-size American oak barrels without charring for 60 months and miniature 6 L oak casks for 24 months. These miniature casks have a higher surface area-to-volume ratio than the larger casks. Although the extraction rates of wood components may have been similar for both types of casks, there would be a higher concentration of wood-derived compounds in the miniature cask distillates in the first 20 months of maturation, showing a higher concentration of total phenols in the miniature casks [74]. Another study showed that bourbons and rye whiskies made under United States regulation and matured in newly charred casks for 2 years increased in intensity as a function of ageing time with aroma attributes, including vanilla, cinnamon, alcohol, and wood. This contrasts attributes in unaged whiskies such as yeast, bread, vegetables, and hay/herbal aromas [43].

The use of oak casks during maturation involves high purchase and maintenance costs. The limited supply of French and American oak has encouraged the search for other types of wood, such as Spanish oak, acacia, chestnut, cherry, elm, and other species, as alternative materials for barrel construction. However, the attempt to find other types of wood shows a lower generation of ageing marker compounds [5]. For this reason, new maturation technologies have been developed in the production of distilled and non-distilled fermented beverages, an example of which is the innovation of accelerated ageing with ultrasonic wave treatments [75] and with wood chips, highlighting its use in studies with apple cider [76], wine [77], cachaça [78], and even whisky [28,54], recalling that these techniques are subject to the regulation of the type of fermented beverage and place of production.

Another type of practice used in the production of Tennessee whiskey is a procedure known as the Lincoln County process, which consists of filtering the newly distilled spirit through maple charcoal before it is matured in newly charred barrels for at least 2 years. One change observed with this type of filtering was the reduction of malty, rancid, fatty, and toasted aromas [79].

7. Conclusions

Whisky production is permissible in various countries as long as local regulations are adhered to within each defined region. Innovative uses of alternative grains and locally sourced materials across the globe are creating new alternatives for whisky that can be officially associated with their country of origin, with a promising outlook as more emerge. It is worth noting that certain aspects of the production process are amenable to research aimed at enhancing the performance of the final product and its sensory attributes while also reducing production costs for the industry. A result of research primarily focused on whisky innovation. The growing production of this distilled spirit worldwide in accordance with regulatory requirements suggests that there is interest in refining the application of new concepts in raw materials or specific stages of the production process, with notable expansion driven by the substantial global output of this spirit.

Author Contributions: Writing—original draft preparation, V.L.E.-L.; writing—review and editing, F.P.M.-S. and H.B.E.-B.; supervision, J.R.V.-C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors thank CONACYT (National Council for Science and Technology of Mexico) for the PhD scholarship number 763182.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Bamforth, C.W. Distilled Alcohol Beverages. In *Food, Fermentation and Micro-Organisms*; Blackwell Publishing: Oxford, UK, 2005; pp. 122–132.
2. Haug, H.; Grasskamp, A.T.; Singh, S.; Strube, A.; Sauerwald, T. Quick insights into whisky—Investigating rapid and efcient methods for sensory evaluation and chemical analysis. *Anal. Bioanal. Chem.* **2023**, *415*, 6091–6106. [CrossRef] [PubMed]
3. Buxton, I.; Hughes, P.S. Chapter 1 Whisky's Historical Development. In *The Science and Commerce of Whisky*; The Royal Society of Chemistry: Croydon, UK, 2021; pp. 1–53.
4. Maitin, B.K. Chapter 6—Indian whiskies. In *Whisky and Other Spirits: Technology, Production and Marketing*; Russell, I., Stewart, G., Kellershohn, J., Eds.; Academic Press: Oxford, UK, 2022; pp. 75–86.
5. Pielech-Przybylska, K.; Balcerek, M. 3—New Trends in Spirit Beverages Production. In *Alcoholic Beverages*; Grumezescu, A.M., Holban, A.M., Eds.; Woodhead Publishing: Duxford, UK, 2019; pp. 65–111.
6. Miller, G.H. What is whisky? In *Whisky Science: A Condensed Distillation*; Springer: Cham, Switzerland, 2019; pp. 1–41.
7. Buxton, I.; Hughes, P.S. Chapter 8 New Whisky Countries and the "Craft" Distilling Phenomenon. In *The Science and Commerce of Whisky*; The Royal Society of Chemistry: Croydon, UK, 2021; pp. 255–284.
8. UK Statutory Instruments. *The Scotch Whisky Regulations 2009*; No. 2890; UK Statutory Instruments: London, UK, 2009.
9. Government of Ireland. *Irish Whiskey Act*; Government of Ireland: Dublin, Ireland, 1980.
10. U.S. Code of Federal Regulations. *27 CFR § 5.22 the Standards of Identity*; U.S. Code of Federal Regulations: Washington, DC, USA, 1969.
11. Government of Canada. *Food and Drug Regulations (C.R.C. c. 870)*; Government of Canada: Ottawa, Canada, 1993.
12. Japan Spirits & Liqueurs Makers Association. *Standards for Labeling Japanese Whisky*; Japan Spirits & Liqueurs Makers Association: Tokyo, Japan, 2021.
13. *Regulation (EC) No 110/2008 of the European Parliament and of the Council*; Official Journal of the European Union: Brussels, Belgium, 2008.
14. *GB/T 11857-2008*; Whisky. General Administration of Quality Supervision Inspection and Quarantine of the People's Republic of China: Beijing, China, 2008.
15. *NOM-199-SCFI-2017*; Bebidas Alcohólicas—Denominación, Especificaciones Fisicoquímicas, Información Comercial y Métodos de Prueba. Diario Oficial de la Federación: Mexico City, Mexico, 2017.
16. *NMX-V-001-NORMEX-2012*; Bebidas Alcohólicas Destiladas—Whisky y Whiskey—Denominación, Etiquetado y Especificaciones. Diario Oficial de la Federación: Mexico City Mexico, 2012.
17. Piggott, J.R.; Conner, J.M. Whiskies. In *Fermented Beverage Production*; Lea, A.G.H., Piggott, J.R., Eds.; Kluwer Academic/Plenum Publishers: New York, NY, USA, 2003; pp. 239–262.
18. Bringhurst, T.A. 125th Anniversary Review: Barley research in relation to Scotch whisky production: A journey to new frontiers. *J. Inst. Brew.* **2015**, *121*, 1–18. [CrossRef]
19. Bathgate, G.N. A review of malting and malt processing for whisky distillation. *J. Inst. Brew.* **2016**, *122*, 197–211. [CrossRef]
20. Bathgate, G.N. The influence of malt and wort processing on spirit character: The lost styles of Scotch malt whisky. *J. Inst. Brew.* **2019**, *125*, 200–213. [CrossRef]
21. Shen, X.; Wang, H.; Zhang, H.; Yao, L.; Sun, M.; Yu, C.; Li, D.; Feng, T. Comparative analysis of the aromatic profile of single malt whiskies from different regions of Scotland using GC-MS, GC-O-MS and sensory evaluation. *J. Food Compost. Anal.* **2024**, *133*, 106465. [CrossRef]
22. Swanston, J.S.; Newton, A.C.; Brosnan, J.M.; Fotheringham, A.; Glasgow, E. Determining the spirit yield of wheat varieties and variety mixtures. *J. Cereal Sci.* **2005**, *42*, 127–134. [CrossRef]
23. Agu, R.C.; Bringhurst, T.A.; Brosnan, J.M. Production of Grain Whisky and Ethanol from Wheat, Maize and Other Cereals. *J. Inst. Brew.* **2006**, *112*, 314–323. [CrossRef]
24. Chiba, Y.; Bryce, J.H.; Goodfellow, V.; MacKinlay, J.; Agu, R.C.; Brosnan, J.M.; Bringhurst, T.A.; Harrison, B. Effect of Germination Temperatures on Proteolysis of the Gluten-Free Grains Sorghum and Millet during Malting and Mashing. *J. Agric. Food Chem.* **2012**, *60*, 3745–3753. [CrossRef]
25. Agu, R.C.; Chiba, Y.; Goodfellow, V.; MacKinlay, J.; Brosnan, J.M.; Bringhurst, T.A.; Jack, F.R.; Harrison, B.; Pearson, S.Y.; Bryce, J.H. Effect of Germination Temperatures on Proteolysis of the Gluten-Free Grains Rice and Buckwheat during Malting and Mashing. *J. Agric. Food Chem.* **2012**, *60*, 10147–10154. [CrossRef]

26. Agu, R.C.; Palmer, G.H. Evaluation of the potentials of millet, sorghum and barley with similar nitrogen contents malted at their optimum germination temperatures for use in brewing. *J. Inst. Brew.* **2013**, *119*, 258–264. [CrossRef]
27. Hernández-Carapia, M.A.; Verde-Calvo, J.R.; Escalona-Buendía, H.B. Influence of temperature and germination time on diastatic power of blue and red maize (*Zea mays* L.) malts. *Emir. J. Food Agric.* **2021**, *33*, 56–66. [CrossRef]
28. Espitia-López, V.L. Elaboración, Estudio Fisicoquímico y Sensorial de la Maduración del Whisky Utilizando Malta de Maíz Rojo y Chips de Madera. Master's Thesis, Universidad Autónoma Metropolitana, Mexico City, Mexico, 2019. [CrossRef]
29. Jack, F.R. 19—Whiskies: Composition, sensory properties and sensory analysis. In *Alcoholic Beverages: Sensory Evaluation and Consumer Research*; Piggott, J., Ed.; Woodhead Publishing: Cambridge, UK, 2012; pp. 379–392.
30. Fukuyo, S.; Myojo, Y. Chapter 2—Japanese whisky. In *Whisky and Other Spirits: Technology, Production and Marketing*; Russell, I., Stewart, G., Kellershohn, J., Eds.; Academic Press: Oxford, UK, 2022; pp. 7–16.
31. Marčiulionytė, R.; Johnston, C.; Maskell, D.L.; Mayo, J.; Robertson, D.; Griggs, D.; Holmes, C.P. Roasted Malt for Distilling: Impact on Malt Whisky New Make Spirit Production and Aroma Volatile Development. *J. Am. Soc. Brew. Chem.* **2022**, *80*, 329–340. [CrossRef]
32. Krakowiak, K.P.; Baxter, I.; Harrison, B.; Pitts, N.; Fergusson, S.; Bell, N.G.A.; Ellis, D.; Mclntosh, R.D. An assessment of spent coffee grounds as a replacement for peat in the production of whisky: Chemical and sensory analysis of new make spirits†. *Sustain. Food Technol.* **2024**, *2*, 1747–1756. [CrossRef]
33. Krakowiak, K.P.; Mclntosh, R.D.; Ellis, D. An assessment of spent coffee grounds as a replacement for peat in the production of Scotch whisky: Chemical extraction and pyrolysis studies. *Sustain. Food Technol.* **2024**, *2*, 92–103. [CrossRef]
34. Mese, Y.; Bryce, J.; Fujii, T.; Takata, R.; Holmes, C.P. Effect of Grist Particle Size Distribution and Wort Turbidity on Ester Composition of Malt Whisky New Make Spirit. *J. Am. Soc. Brew. Chem.* **2024**, 1–8. [CrossRef]
35. Li, J.; Zhang, Q.; Sun, B. Chinese Baijiu and Whisky: Research Reservoirs for Flavor and Functional Food. *Foods* **2023**, *12*, 2841. [CrossRef]
36. Li, W.; Shi, C.; Guang, J.; Ge, F.; Yan, S. Development of Chinese chestnut whiskey: Yeast strains isolation, fermentation system optimization, and scale-up fermentation. *AMB Express* **2021**, *11*, 17. [CrossRef]
37. Zhang, L.; Gao, H.; Baba, M.; Okada, Y.; Okuyama, T.; Wu, L.; Zhan, L. Extracts and compounds with anti-diabetic complications and anti-cancer activity from *Castanea mollissina* Blume (Chinese chesnut). *BMC Complement. Altern. Med.* **2014**, *14*, 422. [CrossRef]
38. Corrêa, A.C.; Marques Bortoletto, A.; Casagrande Silvello, G.; Alcarde, A.R. Novel distilled spirits obtained from combinations of fermented sugarcane juice and malted barley wort. *J. Inst. Brew.* **2021**, *127*, 189–195. [CrossRef]
39. Piggott, J.R. Whisky. In *Current Developments in Biotechnology and Bioengineering*; Pandey, A., Sanromán, M.Á., Du, G., Soccol, C.R., Dussap, C.-G., Eds.; Elsevier: Amsterdam, The Netherlands, 2017; pp. 435–450.
40. Vriesekoop, F.; Rathband, A.; MacKinlay, J.; Bryce, J.H. The Evolution of Dextrins During the Mashing and Fermentation of All-malt Whisky Production. *J. Inst. Brew.* **2010**, *116*, 230–238. [CrossRef]
41. Daute, M.; Jack, F.; Harrison, B.; Walker, G. Experimental Whisky Fermentations: Influence of Wort Pretreatments. *Foods* **2021**, *10*, 2755. [CrossRef] [PubMed]
42. Ndubisi, C.F.; Okafor, E.T.; Amadi, O.C.; Nwagu, T.N.; Okolo, B.N.; Moneke, A.N.; Odibo, J.F.C.; Okoro, P.M.; Agu, R.C. Effect of malting time, mashing temperature and added commercial enzymes on extract recovery from a Nigerian malted yellow sorghum variety. *J. Inst. Brew.* **2016**, *122*, 156–161. [CrossRef]
43. Phetxumphou, K.; Miller, G.; Ashmore, P.L.; Collins, T.; Lahne, J. Mashbill and barrel aging effects on the sensory and chemometric profiles of American whiskeys. *J. Inst. Brew.* **2020**, *126*, 194–205. [CrossRef]
44. Russell, I.; Stewart, G. Chapter 12—Distilling yeast and fermentation. In *Whisky and Other Spirits: Technology, Production and Marketing*; Russell, I., Stewart, G., Kellershohn, J., Eds.; Academic Press: Oxford, UK, 2022; pp. 213–236.
45. Daute, M.; Jack, F.; Walker, G. The potential for Scotch Malt Whisky flavour diversification by yeast. *FEMS Yeast Res.* **2024**, *24*, foae017. [CrossRef]
46. Walker, G.M.; Hill, A.E. *Saccharomyces cerevisiae* in the Production of Whisk(e)y. *Beverages* **2016**, *2*, 38. [CrossRef]
47. Reid, S.J.; Speers, R.A.; Lumsden, W.; Willoughby, N.A.; Maskell, D.L. The influence of yeast format and pitching rate on Scotch malt whisky fermentation kinetics and congeners. *J. Inst. Brew.* **2023**, *129*, 110–127. [CrossRef]
48. Neto, H.B.dA.; Yohannan, B.K.; Bringhurst, T.A.; Brosnan, J.M.; Pearson, S.Y.; Walker, J.W.; Walker, G.M. Evaluation of a Brazilian Fuel Alcohol Yeast Strain for Scotch Whisky Fermentations. *J. Inst. Brew.* **2009**, *115*, 198–207. [CrossRef]
49. Barbour, E.A.; Priest, F.G. Some Effects of *Lactobacillus* Contamination in Scotch Whisky Fermentations. *J. Inst. Brew.* **1988**, *94*, 89–92. [CrossRef]
50. Makanjuola, D.B.; Springham, D.G. Identification of Lactic Acid Bacteria Isolated from Different Stages of Malt Whisky Distillery Fermentations. *J. Inst. Brew.* **1984**, *90*, 13–19. [CrossRef]
51. Van Beek, S.; Priest, F.G. Bacterial Diversity in Scotch Whisky Fermentations as Revealed by Denaturing Gradient Gel Electrophoresis. *J. Am. Soc. Brew. Chem.* **2003**, *61*, 10–14. [CrossRef]
52. Van Beek, S.; Priest, F.G. Evolution of the lactic acid bacterial community during malt whisky fermentation: A polyphasic study. *Appl. Environ. Microbiol.* **2002**, *68*, 297–305. [CrossRef] [PubMed]
53. Reid, S.J.; Speers, R.A.; Willoughby, N.; Lumsden, W.B.; Maskell, D.L. Pre-fermentation of malt whisky wort using *Lactobacillus plantarum* and its influence on new-make spirit character. *Food Chem* **2020**, *320*, 126605. [CrossRef] [PubMed]

54. Tsapou, E.A.; Drosou, F.; Koussissi, E.; Dimopoulou, M.; Dourtoglou, T.; Dourtoglou, V. Addition of yogurt to wort for the production of spirits: Evaluation of the spirit aroma over a two-year period. *J. Food Sci.* **2020**, *85*, 2069–2079. [CrossRef] [PubMed]
55. Grange-Nel, K.L.; Smit, A.; Cordero Otero, R.R.; Lambrechts, M.G.; Willemse, Q.; Van Rensburg, P.; Pretorius, I.S. Expression of 2 Lipomyces kononenkoae α-Amylase Genes in Selected Whisky Yeast Strains. *J. Food Sci.* **2004**, *69*, 175–181. [CrossRef]
56. Hansen, R.; Pearson, S.Y.; Brosnan, J.M.; Meaden, P.G.; Jamieson, D.J. Proteomic analysis of a distilling strain of Saccharomyces cerevisiae during industrial grain fermentation. *Appl. Microbiol. Biotechnol.* **2006**, *72*, 116–125. [CrossRef] [PubMed]
57. Berg, H.Y.; Arju, G.; Nisamedtinov, I. Nitrogen Availability and Utilisation of Oligopeptides by Yeast in Industrial Scotch Grain Whisky Fermentation. *J. Am. Soc. Brew. Chem.* **2024**, 1–13. [CrossRef]
58. Nicol, D.A. Chapter 14—Batch distillation. In *Whisky and Other Spirits: Technology, Production and Marketing*; Russell, I., Stewart, G., Kellershohn, J., Eds.; Academic Press: Oxford, UK, 2022; pp. 247–270.
59. Blaikie, L.; Don, A.W.; Franzen, X.; Fernandez, C.; Faisal, N.; Lin, P.K.T. Valorisation of Whisky Distillery Waste as a Sustainable Source of Antioxidant and Antibacterial Properties with Neuroprotective Potential. *Waste Biomass Valorization* **2024**, *15*, 2333–2343. [CrossRef]
60. Piggott, J.R. Whisky, Whiskey and Bourbon: Composition and Analysis of Whisky. In *Encyclopedia of Food and Health*; Caballero, B., Flingas, P.M., Toldrá, F., Eds.; Academic Press: Oxford, UK, 2016; pp. 514–518.
61. Daute, M.; Baxter, I.; Harrison, B.; Walker, G.; Jack, F. From Fermented Wash to New Make Spirit: Assessing the Evolution of Flavour Characteristics of Scotch Whisky Using Lab-Scale Process Simulations. *Beverages* **2023**, *9*, 37. [CrossRef]
62. Harrison, B. Volatile Compounds Formation in Whisky. In *Volatile Compounds Formation in Specialty Beverages*; Richter Reis, F., Eleutério dos Santos, C.M., Eds.; CRC Press: Boca Raton, FL, USA, 2022; pp. 79–106.
63. Harrison, B.; Fagnen, O.; Jack, F.; Brosnan, J. The Impact of Copper in Different Parts of Malt Whisky Pot Stills on New Make Spirit Composition and Aroma. *J. Inst. Brew.* **2011**, *117*, 106–112. [CrossRef]
64. Lee, K.-Y.M.; Paterson, A.; Piggott, J.R.; Richardson, G.D. Origins of Flavour in Whiskies and a Revised Flavour Wheel: A Review. *J. Inst. Brew.* **2001**, *107*, 287–313. [CrossRef]
65. Esteban-Decloux, M.; Grangeon, H.; N'Guessan, T. Behaviour of volatile compounds during batch multi-stage distillation of whisky: Experimental and simulation data. *J. Inst. Brew.* **2023**, *129*, 192–208. [CrossRef]
66. Conner, J. Chapter 16—Maturation. In *Whisky and Other Spirits: Technology, Production and Marketing*; Russell, I., Stewart, G., Kellershohn, J., Eds.; Academic Press: Oxford, UK, 2022; pp. 291–311.
67. Jack, F. Chapter 18—Sensory analysis. In *Whisky and Other Spirits: Technology, production and Marketing*; Russell, I., Stewart, G., Kellershohn, J., Eds.; Academic Press: Oxford, UK, 2022; pp. 321–333.
68. Luo, M.; Cui, D.; Li, J.; Zhou, P.; Duan, C.; Lan, Y.; Wu, G. Factors in Modulating the Potential Aromas of Oak Whisky Barrels: Origin, Toasting, and Charring. *Foods* **2023**, *12*, 4266. [CrossRef] [PubMed]
69. Vivas, N.; Vivas de Gaulejac, N.; Bourden-Nonier, M.F.; Mouche, C.; Rossy, C. Extraction of phenolics from new oak casks during spirit maturation: Impact on spirit colour. *J. Inst. Brew.* **2020**, *126*, 83–89. [CrossRef]
70. Ashmore, P.L.; DuBois, A.; Tomasino, E.; Harbertson, J.F.; Collins, T.S. Impact of Dilution on Whisky Aroma: A Sensory and Volatile Composition Analysis. *Foods* **2023**, *12*, 1276. [CrossRef]
71. Zhang, D.; Jackson, W.; Dobie, G.; Macleod, C.; Gachagan, A. Innovative non-invasive ultrasound method for whisky cask liquid level measurement. *Measurement* **2024**, *228*, 114345. [CrossRef]
72. Picard, M.; Oulieu, C.; Nonier, M.F.; Vivas, N.; Vivas, N. The role of oak wood in the mint and floral notes of whisky: Identification of common terpenoids by aromatic fractionation. *J. Inst. Brew.* **2023**, *129*, 62–79. [CrossRef]
73. Gollihue, J.; Pook, V.G.; DeBolt, S. Sources of variation in bourbon whiskey barrels: A review. *J. Inst. Brew.* **2021**, *127*, 210–223. [CrossRef]
74. Withers, S.J.; Piggott, J.R.; Conner, J.M.; Paterson, A. Comparison of Scotch Malt Whisky Maturation in Oak Miniature Casks and American Standard Barrels. *J. Inst. Brew.* **1995**, *101*, 359–364. [CrossRef]
75. Prudenza, S.; Foschi, R.; Bax, C.; Capelli, L. An electronic nose for characterising the aroma profile of whisky obtained by a novel accelerated aging process. In Proceedings of the 2024 IEEE International Symposium on Olfaction and Electronic Nose (ISOEN), Grapevine, TX, USA, 12–15 May 2024; pp. 1–4. [CrossRef]
76. Fan, W.; Xu, Y.; Yu, A. Influence of Oak Chips Geographical Origin, Toast Level, Dosage and Aging Time on Volatile Compounds of Apple Cider. *J. Inst. Brew.* **2006**, *112*, 255–263. [CrossRef]
77. Espitia-López, J.; Escalona-Buendía, H.B.; Luna, H.; Verde-Calvo, J.R. Multivariate study of the evolution of phenolic composition and sensory profile on mouth of Mexican red Merlot wine aged in barrels vs. wood chips. *CyTA J. Food* **2015**, *13*, 26–31. [CrossRef]
78. Bortoletto, A.M.; Alcarde, A.R. Aging marker profile in cachaça is influenced by toasted oak chips. *J. Inst. Brew.* **2015**, *121*, 70–77. [CrossRef]
79. Kerley, T.; Munafo, J.P. Changes in Tennessee Whiskey Odorants by the Lincoln County Process. *J. Agric. Food Chem.* **2020**, *68*, 9759–9767. [CrossRef]