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From Soil to the First Sip: Importance of Terroir in Irish Whiskey

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Abstract The term 'terroir' refers to the combination of all environmental elements that influence a crop's phenotype and impart character to distilled spirits through specific identifiable flavour compounds. While terroir's role in undistilled beverages such as wine and beer is well-established, its recognition in distilled spirits encounters scepticism because of the complexity of distillation and ageing processes that potentially obscure the raw material's original characteristics. However, this notion is now being extended to the realm of distilled spirits, with recent research validating the influence of terroir on the distinctive flavours of single-malt Irish whiskey. The Irish distilling sector is rapidly developing, innovating, and boosting the need for local raw materials, which includes exploring grains other than barley, such as wheat, rye, and maize. With a focus on the burgeoning demand for local ingredients and the diversification of grain in whiskey production, this paper reveals the potential for terroir as a marker of authenticity and quality in Irish whiskey. The review delves into the concept of terroir, its implications on Irish whiskey, both malted and grain-based, the diverse factors that shape the terroir, and the limitations of the concept of terroir in distilled spirits. By emphasising innovative practices and current trends, the research provides insights into the benefits of terroir for agricultural producers and distillers alike, while also proposing directions for future investigations to establish terroir more firmly in distilled beverages such as Irish whiskey.

Keywords: *terroir, distilled spirits, organic farming*

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1. Introduction

Terroir, a French term mainly associated with wine, is a significant concept in viticulture as it relates the sensory attributes of the wine to the environmental conditions in which grapes are grown [1]. Terroir is based on the interaction of three main components a) the Physical environment (climate, topography, geology, and pedology), b) biological matter, and c) the culture, and socio-economic condition on which human activities (viticulture and winemaking style) act to attain the expression of terroir [2]. The use of the term 'Terroir' has its roots in ancient France, but it has since expanded globally to distinguish and explore the varied expressions of wine [3]. While Terroir has been a very popular concept in wine manufacturing, its influence on Irish whiskey is a topic of increasing interest and exploration for researchers in the field of brewing and distilling.

Understanding the concept of Terroir in Irish whiskey causes a deep dive into the raw material used and the manufacturing process employed, especially the process of fermentation. Alcoholic beverages comprise a large group that contains varying amounts of potable alcohol (ethanol). Beverages produced on an industrial scale include beer and wine, as well as distilled spirits such as brandy, whisky, rum, gin, cognac, vodka, tequila, and pisco, all have varied ABV%, referred to in Table 1 [4]. Alcohol is produced during the process of fermentation, in which yeast reproduces by feeding on the sugars (e.g., glucose). As they reproduce, the yeasts convert fermentable sugars to alcohol and carbon dioxide through the EMP pathway (Embden- Meyerhof-Parnas).

In this review paper, the authors aim to explore the concept of Terroir in Irish whiskey. The paper aims to consolidate existing research, draw conclusions from previous studies and define a framework for future research direction in the field of terroir in distilled spirits. The uniqueness of Irish grains coupled with Ireland's distinct environmental tapestry, provides a distinct opportunity to examine how these elements impart a signature influence on the spirit's quality and sensory properties. The increasing interest in identifying and preserving the authenticity of regional Irish whiskey further establishes the relevance of terroir studies in this field.

To understand terroir, it is important to understand how different mechanisms of alcohol production can affect the flavour profile of the end products since each processing step can lead to the development of different volatiles.

Table 1. ABV% in each category of drinks [4,5]

DRINKS	ABV%
Spirits	40
Sherry	15-20
Wine	10-15
Strong Lager, beer, or Cider	3-6
Low alcohol, beer, or Cider	1-1.5

There are three different mechanisms through which alcohol can be produced i.e.

Fermentation only

Example: Wine & Perry

Wine is the product of the fermentation of sugar from fruit. Whilst it can technically be made from any sweet fruit, the term wine generally refers to alcohol fermented from grapes or grape juices. There are some other fruits that can be used to make wine, for example, plum, elderberry, and black currant. Non-grape wines are generally called fruit wine or country wine. In terms of wine, the term terroir refers to various factors such as environment, climate, topography, and grape varieties affecting the wine. Terroir is a highly important concept in viticulture because it relates the sensory attribute of the wine to the environmental conditions in which the grapes are grown. In the case of wine, terroir is a sign of quality that farmers look for, they see it as a recognition of environment and landscape values in their practices while for consumers, it is a symbol of authenticity and proximity to the places of production [1].

Brewing and Fermentation

Example: Beer

Beer is a brewed product that contains a small amount of alcohol when finished. Beer is mainly water with some bitter flavour from hops. Beer has the essence of the grain from which it was produced. Usually, it is produced from barley and hops. Hops contribute to the terroir in terms of beer. The character of hops depends solely on the production areas, another factor that contributes to the terroir in beer is the water, which differs from town to town. In the brewing process, the distinctive essence of beer largely stems from the aromatic components in hop oils. The fertilization techniques applied to hops can influence these aromatic qualities by altering secondary metabolic processes and terpene production, thereby impacting the beer's overall quality and its sensory profile. This correlation between hop fertilization methods and the sensory experience of beer was evident in prior research. In one study referenced, consumers were able to discern the quality variations in beers made from hops that were fertilized differently, underlining the critical role that hop fertilization plays in shaping the beer's characteristics [6].

In another previous study by Van Holle et al., 2021 [7], clear biochemical and sensory differences were found between single-hop beers produced with hop pellets from the same variety cultivated in different geographical locations, it was confirmed through the study that terroir-related characteristics of hop batches affect the sensory attributes of beer and those attributes are variety dependent. Besides wine and beer, the concept of terroir holds importance for other food products such as cereals, coffee, honey, and olive oil [7]. In beer, it is observed that malting also produces a wide variety of volatile components. In some studies, around 47 total volatiles were identified during the complete process of malting. [8].

Fermentation and Distillation

Example: Distilled spirits

This review deals with distilled spirits, focusing especially on the implication and existence of Terroir in Irish whiskey. Thus, this section will be explained in deeper detail.

There is emerging evidence to suggest that terroir may affect the flavour profile, aroma, and character of whiskey and therefore establishing the concept of terroir in Irish whiskey can create a much deeper connection between the tillage farmers and the distillers. Terroir, if detected and established in Irish grain-based whiskey, can act as a marketing tool, highlighting the unique characteristics of the region in which the whiskey is produced. This will specifically appeal to customers who are interested in unique and authentic products that help them connect with the region in which the whiskey is produced. Some studies such as one conducted by Martin et al., 2017 [9] provide a robust scientific framework to illustrate the value of terroir in branding strategies for whiskey. For example, the study showed advanced analytical techniques such as UV-Vis spectroscopy combined with partial least squares-discriminant analysis (PLS-DA) that can distinguish between whiskey brands and identify counterfeits. The results and implications of such precise discrimination can also be important for the concept of terroir in whiskey production. By showcasing distinct spectral fingerprinting of various whiskeys, the study conducted by Martin et al., 2017 [9] establishes that the unique characteristics imparted by soil composition, climate, and production methods can be scientifically validated. Incorporating such scientific methodology into the marketing strategy for Irish whiskey could enhance its brand equity. This approach also aligns with the contemporary consumer trend towards transparency and authenticity in food and beverage products. The marketing approach of using terroir-oriented branding should not only appeal to the consumer's sensory satisfaction but should also address their desire for genuine storytelling and product provenance.

Traditionally, Irish whiskey has been produced from malted barley, and through a study conducted by Kyraleou et al., 2021, there has been evidence of terroir in different varieties of Barley (Olympus and Laureate) grown at two different locations (Athy, Co Kildare and Buclody, Co Wexford) in the island of Ireland over two years (2017 and 2018. [10]. It is suggested through the study that barley variety and its growth environment are important in determining the terroir impact on the flavour of Irish whiskey. Based on the findings of the study on malt-whiskey, further studies can be done on different grain varieties such as wheat, rye and maize to study the effects of Terroir in Irish grain-whiskey.

The Irish distilling sector is rapidly developing and innovating, boosting the need for local raw materials. Food Vision 2030, crops 2030, and the Irish Whisky Association (IWA) sustainability roadmap [11,12,13] emphasise the need to improve environmental sustainability in this sector by boosting circular economies, advancing technology, and pursuing carbon neutrality while increasing the use of Irish grain. Organic production

strategies are also gaining momentum, due to delivering more ecologically friendly approaches and have a huge potential to grow in the future. The study of terroir can be extended to different farming practices to examine how farming practices such as organic, conventional, and biodynamic can change the flavour profile of whiskey.

This review paper aims to give an overview of the current understanding of terroir in Irish whiskey and the scope of future research on the concept of terroir in distilled spirits. The conclusions at the end of the review should help in identifying some of the key drivers of terroir in Irish whiskeys such as soil type, grain type, and farming practices involved. The review will also look at the Irish whiskey production process, the problems associated, and the effect of grain type and agronomic practices on the alcohol yield.

2. Whiskey and Its Origin

Whiskey is a spirit that is produced in an extended process consisting of the distillation of fermented grains, ageing, and dilution. Through this process, the distinctive taste of whiskey develops. This alcoholic beverage is generally classified by its country of origin, the nature of the grain, storage conditions and the type of blend, with some countries such as Ireland, and Scotland having GI Technical files [14].

Most of the distilled spirits share a common origin, stemming from basic ingredients such as grapes, grains, or sugar. Historically these spirits were treasured for their supposed therapeutic virtues, with their formulations held by the religious authorities of the era. The generic Latin name given to these distilled products was aqua vitae (water of life). This rings particularly true for whiskey, a name derived from the Gaelic, “uisgea beatha”, which carries the same meaning. The first mention of the aqua vitae was in the book of Odessey. The term “whiskey” varies in spelling- omitting the ‘e’ in Scotland, while it's included in Ireland. Occasionally the definition says that the saccharification must occur via the malted barley’s enzymes alone. The practice of distilling whiskey originated in the monasteries in Ireland and Scotland and evolved into commercial endeavours across continents over centuries. The global expansion of whiskey was not propelled by state intervention alone but also by a striking convergence in market and brand development internationally. The progress in the whiskey industry can be attributed to several key factors:

1. The availability of local technology for distillation,
2. Domestic consumption demands,
3. The ambition and entrepreneurship of key individuals to seize commercial and export prospects, and
4. A dedication to offering a consistently high-quality product [15].

Whiskey has a rich and varied history, with each region around the world contributing unique flavour to the spirit. Different whiskeys are categorised based on the region of the world they come from, the grain used, and the distillation process used by each region. The 5 main whiskey types come from

a). Scotch whiskey- Scotland
b). Bourbon- USA
c). Irish Whiskey- Ireland
d). Canadian whiskey- Canada
e). Japanese whiskey- Japan [16].

In this review, our focus narrows on Irish whiskey for a more in-depth study as Irish whiskey continues to experience steady growth globally.

3. Irish Whiskey

Before delving deeper into the concept of terroir, it is essential to understand that the manufacturing process of whiskey plays an active part in the creation of terroir, therefore understanding the nuances of Irish whiskey production is important before delving into the complexity of flavour developments at each stage. Minor alterations in the processing can influence the volatile aromatics in whiskey [17].

3.1. Overview of the Irish Brewing and Distilling Sector

The brewing and distilling sector of the Irish drinks industry has recorded tremendous growth over the years with an average growth rate of 4% per annum. Beer and spirits in the Irish drink market have a market share of 39% and 22%, respectively. Currently, Ireland is the 7th largest exporter of beer in Europe and the 8th largest producer of spirits in Europe, producing an average of 800 million litres of beer and 190 million bottles of spirits annually. The growth in the sector's output has been consistent since 2014 and can be attributed to the increase in popularity of Irish brands of beer and spirits and a proportionate increase in the total number of breweries and distilleries in the sector [18].

The Irish brewing industry witnessed tremendous growth in the microbrewery sector, expanding from 15 microbreweries in 2012 to up to 75 microbreweries in 2018. While in the distilling industry, the total number of distilleries in Ireland grew from 4 distilleries in 2010 to 38 distilleries in 2020. The growth of beer and spirits production in the Republic of Ireland, despite being positive, has taken a toll on processing input requirements and utilisation by the sector. For instance, it is estimated that around 300,000 tonnes of grains are used annually to support the Irish brewing and distilling industry, of which 220,000 tonnes are barley malt. To meet the demands of the industry, there has also been a commensurate rise in the importation of large amounts of grains every year. From 2000 to 2018, the number of cereals imported for brewing and distilling increased at a linear rate of 64,000 tonnes per year, reaching 1.6 million tonnes in 2017. Every year, the Irish distilling sector needs about 115,000 tons of imported maize. Ireland's net export position for malt, which was over 40,000 tonnes yearly in the early 2000s, has decreased. Currently, Ireland is a net importer of malt as opposed to its net exporter position in the early 2000s. As a result, one of the key issues facing the Irish brewing and distilling sector is the establishment of a strong base of producers providing input for the sector on a sustainable level. Addressing sustainability is now a key challenge for the sector, with the need for a stable and

sustainable input base growing increasingly evident, there is a need to enhance the use of Irish-grown grains by master's distillers generating an alternative market for tillage farmers [18].

Due to the expansion and increase in the number of Irish whisky distilleries and microbreweries, investments in the Irish brewing and distilling industries have seen significant growth rates over the past ten years. Ireland's beverage export, encompassing beer, spirits, and cider reaches over 125 destinations across the world, contributing to 75% of the nation's total beverage export. The unique quality and branding of these exports have carved a niche in the global market, making them less susceptible to general market fluctuations. The US and UK are the primary markets for these exports, especially for spirits. Within Ireland, vodka enjoys the highest sale percentage as referred to in Figure 1, closely followed by Irish whiskey and a variety of other spirits such as gin and rum [19,20].

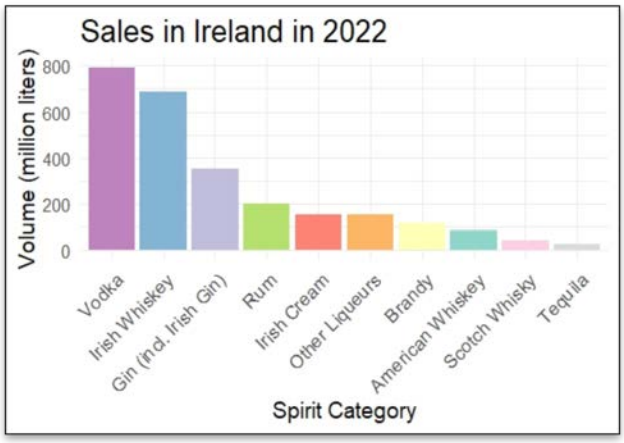

Figure 1. Spirit Market Report-Percentage of sales in 2022 modified from [19]

3.2. Manufacturing Process for Irish Whiskey

Irish whiskey is also recognized and commercialized by its Geographic Indication (GI), meaning that it can only be branded as such if it is produced following a standardized methodology on the island of Ireland. The Irish whiskey industry is expanding quickly, innovating, and diversifying its product line as more distilleries are opening and new ones are entering the market regularly [13].

Barley and maize dominated the Irish distilling industry for many years, but today other grains, including wheat and rye, are gaining popularity. Each year, Ireland produces 600,000 tonnes of wheat. [13,21]. Wheat is considered good for producing significant alcohol yields (AY) since it frequently contains a lot of starch and little protein. Irish whisky is made from malted barley alone or with a mixture of un-malted barley, wheat, rye, and oats. In the manufacturing process, the grain is converted into beer except for the omission of hops and distilled to obtain a distillate containing 80% alcohol by volume. It is then diluted with water and stored in charred barrels. After the desired period of ageing, the whisky is adjusted to the required alcohol strength and bottled. Irish whiskey is generally categorized into three categories according to the Irish Whiskey Technical file [22].

a) **Pot still Irish Whiskey/ Irish pot still whiskey:** The ingredients used to create "Pot Still Irish Whiskey/Irish Pot Still Whiskey" are natural, currently peated malted barley, and other un-malted grains, water, and yeast are used. Other natural enzymes may also be used in the brewing and fermentation stages. The un-malted barley is an essential ingredient of "Pot Still Irish Whiskey/Irish Pot Still Whiskey" as it gives both a distinctive spicy flavour to the whiskey and influences the texture by giving the whiskey a typical creamy mouth feel. The mash should contain at least 30% malted barley and at least 30% un-malted barley and be a) saccharified by the diastase of malt contained therein, with or without other natural enzymes; b) fermented by the action of yeast; c) distilled in pot stills in such manner that the distillate has an aroma and taste derived from the materials used [22].

b) **Malt Irish whiskey:** Malt Irish whiskey is made from natural raw materials, 100% malted barley, water and yeast. Other enzymes also be used at the brewing and fermentation stages. Malted barley can be peated or unpeated, because of using 100% malted barley, the whiskey has a distinctive smooth, velvet, full, and oily texture, with a malty and sweet taste. Malt whiskey is a spirit made from 100% malted barley and

- saccharified by diastase of malt contained therein, with or without other natural enzymes.
- Fermented by the action of yeast
- is distilled in the pot stills in such a manner that the distillate has an aroma and taste derived from the material used.

c) **Grain Irish whiskey/Irish grain whiskey:** The whiskey is produced from malted barley (cannot be more than 30%) and includes whole un-malted cereals usually maize, wheat, rye or barley. Other natural enzymes can also be used at the brewing and fermentation stage. The mash should be

- Saccharified by the diastase of the malt contained therein, with or without other natural enzymes.
- Fermented by the action of yeast
- Distilled in a column still in such a way that the distillate has an aroma and taste derived from the materials used in the column distillation method.

d). **Blended Irish whiskey/ Irish blended whiskey:** It means a blend of two or more whiskey from Irish pot still whiskey, Malt whiskey and grain-based Irish whiskey. The whiskey used must be produced in Ireland and should be produced according to the steps described above. The main idea of blended whiskey is to smooth out the irregularities from the different distilleries. This whiskey largely depends on the skills of the blender, they can come up with different combinations to produce an end product with a new taste that retains or enhances the component flavours but the whole is inseparable from the parts.

Stages of the Production process

Brewing stage: Cereals are milled and mixed with water. Other enzymes can be used at the brewing or fermentation stage. The mash is converted into wort or brew liquor, which is further fermented. Irish Malt whiskey or Pot still whiskey is brewed in a batch traditionally. Grain-based whiskey is brewed from Maize or Wheat and Malted barley. The cereals are converted into ground flour and heated to a high temperature before conversion.

Fermentation stage: The resulting liquid after the brewing process is cooled and pumped to fermenters where yeast is added and the sugars in the wort are converted to alcohols and other congeners. This fermented liquid is traditionally termed a "Wash".

Distillation stage: It is a process that enables the separation and refinement of the spirits from the incoming wash. There are two separate technical processes related to the type of spirit distilled.

a) **Pot still distillation:** The fermented wash is added in discreet batches into the first copper pot still. As the temperature in the still is raised, alcohols and congeners are removed. These vapours are condensed in a condenser and collected into a receiving vessel. This resulting first stage distillate is termed 'Low Wines'. The application of particular cutting strengths, as identified by the Distillers, determines the character of the Low Wines in terms of flavour intensity. Each distillery can either opt for two-stage or three-stage distillation process

- Two-stage will involve pumping low wines and recycled second distillates to a second-stage pot still. Once heat is applied to the pot still, initial distillate is obtained. The first running is called Forehshots or heads and is collected separately. The middle cut also called the heart is selected as the spirit goes for maturation. The middle cut is responsible for smoothness, texture and flavour. After obtaining this 'middle cut', the distillation continues and the resulting alcohol, called feints, is collected and recycled in subsequent distillation sequences.
- Where triple distillation is employed the first distillate (low wines) is distilled into a second-stage spirit called Feints. This second distillate is further distilled for a third time in a Spirit Still. Triple distilled spirit obtains its character from the choices and methods used to select the center cut at the third stage and not at the second stage.

"Pot Still Irish Whiskey/Irish Pot Still Whiskey" is usually distilled in large pot stills. The large stills contribute to a unique range of reflux ratios that lead to the formation of a distinct flavour and aroma profile in the spirit. "Malt Irish Whiskey/ Irish Malt Whiskey" is usually distilled in smaller pot stills.

b) **Column stills distillation:**

There are 2 types of distillation columns:

- 2-stage distillation columns: Consists of the beer column and rectifying column.
- 3-stage distillation columns: Uses beer column, an extractive distillation column, and a rectifying column. This enables the removal of more fractions and the resulting spirit can be quite fragrant and more lightly flavoured.

Grain whiskey can be distilled through only the column still distillation

- Involves passing a continuous flow of wash down through the series of perforated plates within the distilling column.
- Steam is applied at the bottom of the plates, removing alcohol and other congeners from the wash. The alcohol-laden vapour is cooled in a condenser at the top of the column.
- The first-stage vapour is distilled a second time through a secondary column. The flavour intensity of this spirit is influenced by the removal of the overheads from the condenser section of the column. Side stream fractions are also removed.
- Grain spirit is less intense in flavour as compared to the pot still distillates.
- Final spirit removed usually has a strength of 94.5% volume.

The final spirit is usually assessed by the trained quality control panel before releasing for subsequent maturation. This guarantees a uniform quality check on the consistency of the distillate.

Maturation stage: Uisce Beathe or Irish Whiskey must be matured in wooden casks, such as oak, only on the island of Ireland, and the ageing should minimum be three years. New casks and casks which may have been previously used to store other alcoholic beverages, for example, Madiera, Sherry, port or Bourbon are used.

Using seasoned casks means that the spirit is not overpowered by excessive wood extracts and tannins but delivers a complex but balanced character to the spirit and enables the development of flavour attributes. Colour development, which varies in colour from pale gold to dark amber, depends upon the maturation casks chosen. Irish Whiskey/ Uisce Beatha Eireannach/ Irish Whisky shall not be exported from Ireland in wooden casks, such as oak or other wooden containers, which may cause further maturation of "Irish Whiskey/ Uisce Beatha Eireannach/ Irish Whisky" outside of Ireland or Northern Ireland.

Bottling Stage: Bottling may occur outside Ireland. Where "Irish Whiskey/ Uisce Beatha Eireannach/ Irish Whisky" is bottled offshore, it is shipped in inert bulk containers. The subsequent water used in the final product is demineralized to preserve the organoleptic characteristics of the "Irish Whiskey/ Uisce Beatha Eireannach/ Irish Whisky". Any bottling occurring outside of the island will be subject to company controls and official verification, which will ensure the product's safety and integrity [22].

4. What Shapes Terroir?

Terroir is a combination of various elements, such as climate, soil, and geography, that influence the taste and aroma of the finished product. Volatiles that affect the taste and aroma are usually analysed by gas chromatography (GC), a method which has been improved. The GC method has evolved in all areas: column selection, carrier gas selection, temperature programming, injector selection, injector temperature, detector selection, and detector temperature. Modern chromatographic techniques have evolved to employ sophisticated and innovative gas chromatography (GC) procedures for identifying aromatic compounds. Techniques such as solid-phase microextraction mass spectrometry (SPME-MS) and rapid gas chromatography electronic nose (GC-E-Nose) applications have been utilized and evaluated for their effectiveness in distinguishing between spirits with distinct aromatic classifications and regions of production [23].

Whiskey contains a great variety of flavour compounds belonging to different chemical families such as higher

alcohols, ethyl and isoamyl esters, acetates, fatty acids, ketones, monoterpenes, C_{13} nor isoprenoids and phenols. Whiskey aroma is derived from each step in the production process which includes raw materials, fermentation, distillation, and barrel ageing [24]. New make spirit is the product post-distillation and pre-cask maturation, it must be stored in the wooden casks for at least 3 years before bottling and retailing [10]. Although every step of the alcohol production plays a vital role in establishing the flavour complexity of the distilled spirit, the cereal crop imparts a distinctive sensory profile, which is attributed to the geographical origin [25].

chemical compounds that lead to the characteristic flavour/ aroma of the whiskey.

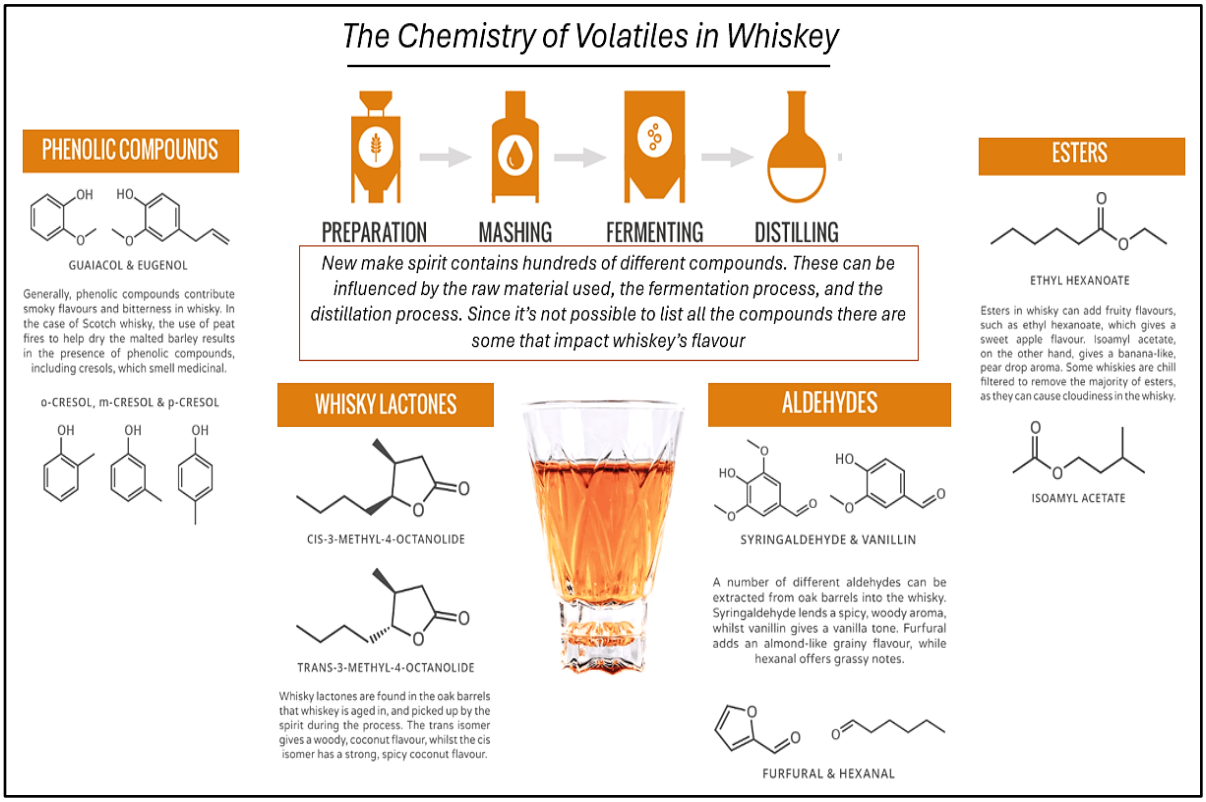

Figure 2. Chemical composition of whiskey contributing to the aroma profile modified from [56]

a). Fatty acids and their corresponding esters:

Interestingly, both whiskey and cognac contain the same volatile components, but they differ only in quantity. In the case of cognac, the fatty acids and their corresponding esters are mainly formed by the yeast during the fermentation process, which contributes to the typical fruity and flowery odour notes. [17]. Fermentation by yeast undertakes in anaerobic conditions to produce the ethanol but still, oxygen's presence is pivotal during fermentation, enabling yeast to produce fatty acids and sterols which are essential for cell membrane development. The fatty acid growth is limited unless the wort solution is provided with oxygen in direct form [26,27].

Fatty acids of the medium chain such as hexanoic, octanoic, decanoic, and dodecanoic are initially present in the wort in smaller amounts but eventually accumulate during fermentation depending on various factors such as temperature oxygen availability and yeast strain used, they contribute to the fatty, waxy and sour characteristics when present in high concentrations, The medium chain Fatty acid's development is directly influenced by the yeast activity so the strain used plays a very important role in a desired characteristic, some of these medium chain fatty acids may also be degraded from the longer chain fatty acids such as palmitic and myristic acids [28].

b). Corresponding esters:

Short, medium, and long chain fatty acids can lead to the formation of esters during active growth or exponential phase of yeast also known as primary fermentation by the process of enzymatic condensation/esterification. Esters are a major contributor to the flavour of the whiskey. Acetate esters come into being when acetic acid undergoes a reaction with ethanol or other types of alcohol, with ethyl acetate being the predominant type because of ethanol's relative abundance [27,29]. Additional ester acetates also play a significant role in defining the flavour spectrum of whiskey. These include 2-phenylethyl acetate, which contributes floral and rose-like notes, and 3-methylbutyl acetate, commonly referred to as isoamyl acetate, that imparts banana or pear drop flavours [30,31] [10,24]. Other category of esters in whiskey is the medium chain ethyl esters. Both of these esters are formed by the yeast intracellularly, and because of being lipid soluble and low molecular weight they can diffuse through plasma membrane through diffusion medium. Diffusion of acetate esters is rapid due to their smaller size while that of medium chain ethyl ester is slow and depends on the number of carbon atoms [32].

c). Aldehyde and Furfurals

The grain-derived compounds can also undergo some other reactions such as the Maillard reaction and Strecker degradation during whiskey production, giving out the aroma and unique flavour to the whiskey [33]. Furfural is part of the feint (the final part of distillation) and has also

been detected in raw material and the wort for the beer [10]. This component can contribute to the roasty aroma of the new make spirit. Furfural is formed during distillation due to the dehydration of fermentable sugars (pentoses) caused by heating during the Maillard reaction.

Amino acids, primarily derived from malt, play a role in the generation of aldehydes during the mashing and boiling of wort. These aldehydes are further broken down by alpha-carbonyls produced during the Maillard Reaction, which results in the amino acids undergoing deamination and decarboxylation processes. The amino acid can undergo either Strecker degradation with an α-dicarbonyl or an Amadori rearrangement with an α-hydroxy carbonyl, both of which produce Strecker aldehydes. Amadori Strecker aldehydes further produce brown, high molecular-weight polymers called melanoidins [34,35]. Aldehydes, including those originating from Strecker synthesis and fatty acid processes, serve as crucial intermediate substances, particularly in the formation of various alcohols [28,36,37,38]. Alcohols containing more than six carbon atoms are generated from aldehydes through a series of enzyme-driven steps identified as the lipoxygenase pathway [39,40]. Alcohol oxidation to aldehyde is often in equilibrium, explaining that the high level of aldehyde can represent fluctuations in whiskey processing. As intermediate compounds, aldehyde can also indicate incomplete attenuation during fermentation, as high concentration is common in low ABV spirits [30].

During the lipoxygenase pathway, certain lactones like γ-nonalactone, which originate from hydroxy fatty acids present in malt, are formed and, contribute a coconut-like aroma to the spirit when the temperature is high. [41].

In the case of Malted whiskey, aldehydes, particularly methional, heptanal, (E) 2-octenal, hexanal, and decenal contribute to the characteristics of whiskey [10]. Aldehydes provide a variety of characteristic odour to whiskey. For example, Methional belongs to the category of vegetal odour and is derived from methionine through Strecker degradation. In a study on Spanish wine, methionine has been found to have a negative effect of overpowering the fruity aroma of the beverage. Hexanal is another important compound that is said to have a green vegetative odour and can generally be impacted during the process of malting, fermentation, and distillation [42,43,44]. Apart from these other important aldehydes such as trans-2-octenal has a metallic, mushroom-saw dust-like aroma, and trans-2-nonenal has a cardboard-like aroma [28,45,46].

d). Ketones

Ketones are generally the part of the volatiles produced from the foreshots during distillation. Many ketones are found in foreshots but due to their high odour detection threshold, they are thought to not significantly contribute to the aroma of the whiskey [47]. Some of these ketones have a synergistic effect for example β-damascenone, an unsaturated, cyclic ketone, is known to interact collaboratively with other compounds to enhance certain odours such as fruity, and minimise certain others such as vegetal note, which is considered a negative note [10]. Some Ketones such as vicinal diketones (VDKs) are the key flavour congeners, produced during amino acid metabolism at the stage of fermentation. Diacetyl (2,3-butanedione) and acetylpropionyl (2,3-pentanedione) stand out as primary volatile diacetyl compounds (VDKs) generated during this phase, contributing to the rich and appealing scent reminiscent of butterscotch [30,31]. In fermented beverages, diacetyl notes can be perceived both as negative or positive depending on the style of the end product. For example, in lager beers, known for their fresh and clean flavour profiles, diacetyl is invariably considered as an off note [49].

e). Acetals

Acetaldehyde, a pivotal and very reactive aldehyde that contributes to the formation of diverse flavour compounds, is formed through the yeast's decarboxylation of pyruvate as an intermediary step in ethanol creation, or through dehydrogenation of ethanol [48]. Acetaldehydes are very reactive and react with ethanol to give diethyl acetals (1,1-diethoxyethane/acetaldehyde diethyl acetal), which have low aroma detection threshold and are known to give the ethereal, sweet, and nutty odour [29].

f). Sulphur

Many of these sulphur compounds are formed during malting, fermentation, and distillation as referred in Figure 3. Some of these compounds decrease during distillation and maturation. Sulphur compounds such as Dimethyl sulphide (DMS) Dimethyl sulfoxide (DMSO), dimethyl disulphide (DMDS), dimethyl trisulphide (DMTS), and H2S (hydrogen sulphide) mainly can form during fermentation, generally the formation is due to two main reactions that is biosynthesis of cysteine, and methionine, and reduction of sulphate salts from the wort [50]. At low level sulphur compounds can have positive effects but the negative effects tend to increase with increase in their concentration. There have been few experiments on reducing their amounts during upstream processes [51].

Terroir critics may claim that the flavour of the whiskey is majorly affected by the ageing process therefore the grain type may not be a strong factor for flavour contribution, but some studies suggest that both aged and fresh make spirits have volatile aromatic profiles associated with the botanical origin of the raw material [25]. All this information gives a strong background to claim that whiskey terroir can be an interesting area for researchers in the field of brewing and distilling.

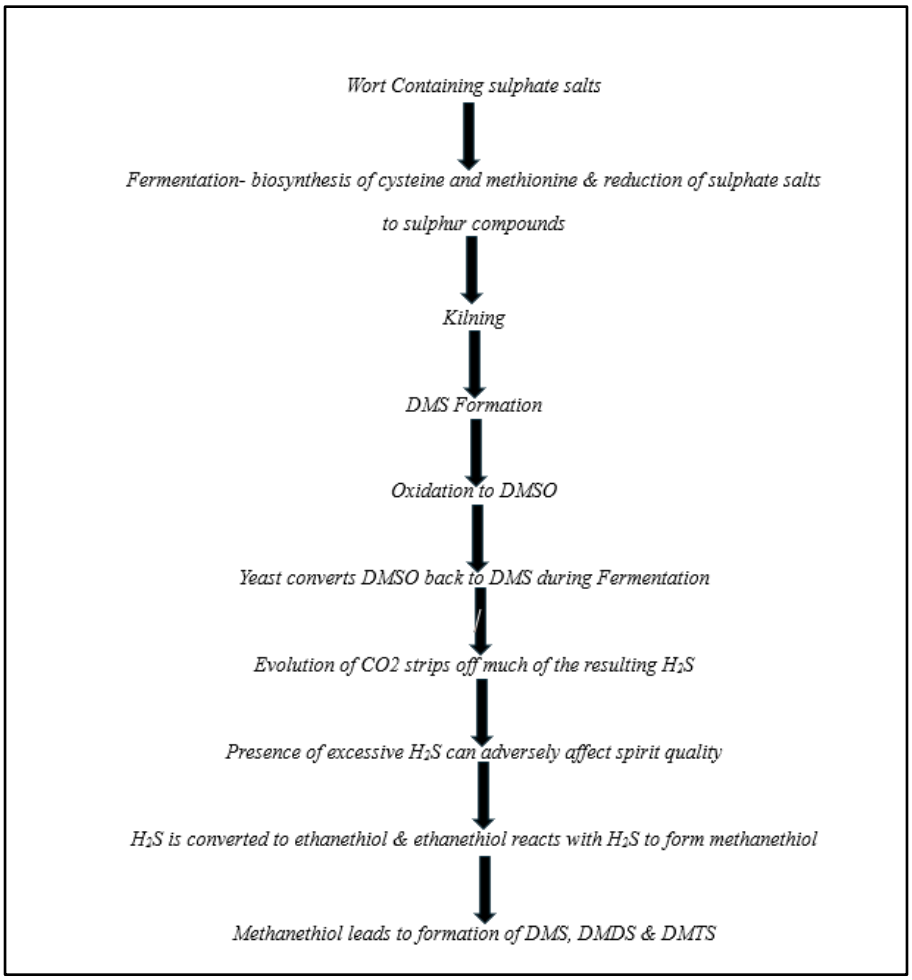

Figure 3. Flow chart showing the development of sulphur compounds during fermentation [50,51], modified from [17]

5. Potential Factors Affecting the Terroir in Irish Whisky

Amongst many potential factors that can affect the terroir in Irish Whiskey, there are a few such as soil, climate and grain type that are known to have a significant effect on the flavour profile of distilled spirits. This section delves into how soil composition and climatic conditions affect the directiveness of Irish whiskey, drawing comparisons to the existing wine terroir principles.

5.1. Soil, Climate, and their Impact on Terroir of Irish Whiskey

5.1.1. Soil: It has been observed through many research papers on terroir in wine that the type of soil and its interaction with climate can affect the flavour profile of the beverage. In viticulture, the soil influences the vine development and grape ripening through soil temperature, water supply, and mineral supply. It is seen that soil temperature (relative to air temperature), soil water holding capacity (relative to rainfall and potential evapotranspiration) and soil nitrogen availability are the key drivers for the type of wine which is intended to be produced. The terroir effect is sometimes attributed in well-known wine literature to vine roots going down into the soil for meters to collect specific minerals that confer typically to wine [1].

In Irish whiskeys, the type of soil used to grow a particular grain can have a huge impact on the flavour and odour profile. Soil pH is a key factor in nutrient uptake and affects availability by changing the form of micro and macronutrients in the soil. The amount of nutrients in the soil also plays an important role in determining flavour characteristics. For example, soil with higher pH and increased amounts of Ca, Mg, and Mo can lead to whisky with toasted almond notes and a malty, biscuity, and oily finish. Whereas soil with a low pH, results in high amounts of nutrients such as Fe, Cu, and Mn, leading to floral and lighter whiskey with the flavour of fresh fruitiness [10]. Previous studies claim that the sensory perception of new spirits used in creating single malt whisky is significantly influenced by environmental factors, including soil nutrients and current seasonal weather patterns. Also, the studies raise the possibility that environmental elements, such as soil, may be significant in the manufacture of single malt whisky by indicating the existence of a "Terroir" impact on the flavour of new make spirit. To evaluate the significance of terroir in whiskey beyond the ageing phase, further research is necessary to better understand the specific environmental impact of soil on barley growth.

5.1.2 Climate: Apart from soil, climate plays a pivotal role in defining terroir. In the case of wine, topography

plays an important role in determining the flavour of a wine, which includes slope, altitude, and nearby physical features. Each of these has an impact on the flavour profile. For example, steeper, south-facing slopes drain well and get stronger sunlight, while higher altitudes have colder nights and can cause the wine to taste more elegant. Lakes and large bodies of water can provide a moderating influence, while mountain ranges can offer protection against wind and other elements [52]. The climate in which the grains are grown can also influence the flavour profile of whiskey. While temperature is important for terroir, the whole climate must also be considered. Rainfall, sunlight, soil type & quality, and temperature are some of the factors to consider when considering environmental factors that affect the growth of wheat, rye, maize, and barley.

While there has been little research done on whiskey terroir as compared to wine, we can still draw some hypotheses based on the findings of wine terroir.

1). The type of soil used to grow barley, wheat or rye for the production of malted or grain-based whiskey can have an impact on the flavour profile. For example, high peat levels in soil can lead to smokey and earthy flavour to whiskey. As in the case of wine, nitrogen plays a crucial role in the type of wine intended to be produced, similarly for whiskey and the grain associated with its production can also be influenced by the type of soil rich in a particular nutrient.

2). The climate in which the grain is grown can also possibly affect the flavour profile of the whiskey. It can be assumed based on the previous research on wine terroir that grains grown in cooler and humid climate can lead to different flavour profile of whiskey as compared to grains grown in the drier and warmer climate.

These are speculative hypotheses, and they offer some starting point for exploring the impact of soil and climate on the terroir in Irish whiskey.

5.2. Grain Varieties and Their Effect on the Terroir

Kyraleou et al., [10], looked at the effect of barley cultivar and growing region on terroir. It was observed that grain types do affect terroir, and this study underscores the significance of taking "terroir" into account in the production of alcoholic beverages outside of the wine business and offers useful insights for the whiskey industry on the impact of environmental elements on product quality. There has also been some research done to explore the potential impact of different varieties of corn on the flavour and alcohol yield of Bourbon whisky, which concluded that variety and terroir can significantly influence the sensory characteristics of whisky and also suggests the importance of scientifically evaluating corn genetics for developing better whisky [33]. More research is also required to examine how grain composition can affect alcohol yield, production, processability issues, and terroir. The findings of these results can help in optimising the best grain composition that is required to produce high-quality Irish whiskey.

5.3. Microbial Terroir and the Need for Future Research?

The concept of microbial terroir is based on the uniqueness of the soil microbiome at a particular site that can affect the growth of the vine, the composition of the fruits, and the characteristics of the wine to create a distinct sensory profile. Recent studies have used advanced genetic-based techniques suggesting that soil microbial composition and activities are linked to wine terroir [53].

However, in whiskey, Microbial terroir is an emerging area for research and its finding would hold a very important area of innovation for whiskey producers as they will be able to reflect the natural diversity of the surroundings. The microbial terroir in the case of Irish whiskey is essential in determining the flavour character of the spirit. Irish whiskey's distinctive smells and scents can be attributed to a variety of native yeasts, bacteria, and fungi. For instance, using malted barley that has been dried over peat fires can give the whiskey a smoky flavour, and using local yeasts throughout the fermenting process might provide flavour components. Overall, a particular region's microbial terroir can have a significant impact on the flavour and fragrance profile of Irish whiskey, resulting in a special and distinctive product that represents the environment and culture of the place.

5.4. Farming Practices

The type of farming practice can also affect the terroir in Irish whiskey. For example in case of organic farming, there is use of typically less amount of synthetic fertilizers and pesticides, which helps in maintaining the natural healthy balance of soil and create a suitable growing environment for the grain crops. This can lead to a product with richer and wider complex flavour profile. Harvesting process can also affect the terroir in Irish whiskey for example the harvesting season or the methods of harvesting (manual or machine) can also affect the quality of final product.

6. Implications of Terroir on Sensory Characteristics of Irish Whisky

The presence of Terroir in Irish whiskey will help in the establishment of unique flavour profiles that are specific to the region in which the grain is grown. In addition to the taste, terroir will also affect the aroma profile of the whisky as it is observed through previous studies that the type of soil, water, and environmental factors can contribute to the aroma of whisky, resulting in distinctive and complex scent profiles.

GC-MS can be used to establish the terroir in Irish whiskey by analysing the volatile compounds present in the whiskey and comparing them to the compounds found in the local environment. The fermentable substances such as long chain fatty acids, organic nitrogen, sulfur compounds, and many other components take part in the different biochemical process which leads to the formation of volatile components as a by-product, influencing the

organoleptic property of the whiskey [54].

The precise ingredients that give Irish whiskey from a given region its distinctive flavour and fragrance profile can be found using GC-MS, which analyses the volatile compounds in the whiskey. In order to develop a distinct terroir, GCMS can also be utilized to determine any variations in the volatile chemicals contained in whiskeys from various places. However, GC-MS is commonly used for qualitative or quantitative analysis of volatile compounds, it is noted that only a small proportion of volatile compounds can contribute to sensory perception. To address this limitation, some studies such as [10] was done using gas chromatography olfactometry (GCO) as an additional sensory evaluation tool, which involves trained assessors sniffing the eluent from the GC column containing separated volatiles and classifying their aroma. The quantitative data of the volatiles from different samples can undergo multivariate analysis such as principal component analysis to determine the effect of the location, year and other factors that can contribute to terroir.

By carefully paying attention to the terroir in Irish whiskey, distillers will be able to understand the flavour profile of a whiskey better and thus will be able to exert control over it, this will in return give a high-quality distilled product. The existence of terroir and understanding the factors that affect it will help to optimise the parameters that can have an impact on the quality of Irish whisky. Terroir will help differentiate Irish whisky from the rest of the world, as it will bring the taste of the land to the first sip. Distillers will be able to emphasize the unique characteristics of the environment in which the grain for their whiskey is grown and will be able to use it as a marketing tool to differentiate their product in the market.

7. Future of Terroir in Irish Whisky: Future Developments and Challenges?

The previously existing research on terroir in Wine can be a very reliable source to conduct more studies on terroir in Whiskey. There is a great deal of potential for further research on the terroir in distilled spirits. Some of the future developments can be on:

7.1. Potential Areas for Research on Terroir in Irish Whiskey

a) Focus on locally sourced grains grown in Ireland. This will also include exploring grains other than just barley, for example, wheat, rye, maize, or a combination of grains. This practice will also reduce the burden on just one grain. The usage of different grains can reduce the risks associated with climate change and environmental factors.

b) Microbial Terroir in Whisky: In the same way yeast strain or microbial load during ageing can have an impact on Terroir in wine, there can be some findings for distilled samples such as whiskey too. There is a huge scope to investigate the quantitative relationships between the Site's natural microbial load, yeast strain and the effect on terroir in whiskey.

c) Impact of Organic and biodynamic practice: Food Vision 2030 [11], Crops 2030 [12], and the Irish Whisky Association (IWA) sustainability roadmap [13] emphasise the need to improve environmental sustainability in the Irish brewing and distilling sector by promoting circular economies, advancing technology, and pursuing carbon neutrality while increasing the use of Irish-grown grains. Organic production strategies are gaining momentum due to delivering more ecologically friendly approaches, so comparing grains based on different farming practices will be a great opportunity for research to evaluate how different agricultural techniques can yield illuminating results on alcohol output and terroir in whiskey.

d) Enhancing transparency for customers and brand connection: With the establishment of the terroir in Irish whisky, customers will locate where the raw material is sourced and how the environmental factor has influenced their glass of whisky. It will foster the connection and awareness with the product.

e) Promoting local agriculture: The establishment of terroir in their bottles will help distillers develop a connection between customers and the land where the grain for the whisky is grown. This will lead to distillers sourcing their grains from local farmers and will reduce the carbon footprint and will also be beneficial for customers who are interested in sustainable products.

f) Molecular basis of the Terroir: Previous studies do not delve into the molecular basis of Terroir and further research is required to better understand the specific environmental impact on barley growth and the management and processing thereof in accordance with genetic, physiological, and metabolic mechanism contributing to the expression of terroir in distilled beverages such as whiskey. In the case of wine, the genetic background has been reported as the most important factor affecting the quality of berry species. Agricultural practices have been reported to slightly affect sugars, organic acids, and free amino acids in fruits such as apples. It can be postulated that the terroir effect can result from directly triggered crop response to stressors, and epigenetic-mediated indirect biochemical modifications. It has been demonstrated that agronomic and pre-harvest elements such as cultivation methods, plant age, and environment can modify the sensory qualities and nutritional value of certain fruits [55].

7.2. Potential Challenges with the Development of Terroir in Whisky

a) **Large-scale development of terroir:** To date, studies on Terroir in Irish whisky have looked at the small-scale development of terroir. It can be a challenge in the future to replicate the same development for large-scale commercial production.

b) **Homogeneity of grain sources:** The idea of terroir originates mainly from the soil and the environment in which a particular grain is grown. It can be a difficult problem in the future to source grains only from a single place and maintain their uniqueness.

c) **Standardization of Terroir terminology:** It can be difficult for producers and consumers to completely comprehend and appreciate the value of terroir due to

the lack of standardized vocabulary and techniques for assessing and expressing it in terms of flavour profile.

8. Conclusion

The significance of terroir in the creation of whiskey is still a topic of intense discussion among whiskey enthusiasts and industry experts. Some argue that the impact of terroir is exaggerated and that other elements, such as the kind of barrels used for ageing, have a more significant effect on the taste and quality of the final whisky, while others say that terroir is an important aspect of whisky manufacturing and is crucial to developing different flavours. The complexity of whiskey makes it difficult to study how terroir affects the end product. Whiskey is normally manufactured from a combination of grains and aged for several years, unlike wine, which is derived from a single variety of grape and can be produced in a single vintage. This can make it challenging to pinpoint the precise role that terroir played in the creation of the final product.

Despite all the criticism and potential challenges, there is a rising interest in researching how terroir affects whiskey. In addition to testing the effects of various soil types and microclimates on the flavour of their products, some distilleries such as Waterford distillery in Ireland are experimenting with the use of locally sourced grains and water and the chemistry of finished products. Advanced sensory analysis methods can also be used to improve understanding of how terroir affects the flavour and aroma of whisky. Overall, there is no question that terroir plays a significant role in producing a distinctive product, even though its impact on the manufacture of whiskey is still up for debate. After conducting the review of various literature present around the concept of terroir in whisky. It can be concluded that the concept of terroir can be important for the production of other distilled spirits due to the use of specific grain varieties that grow under different climatic conditions. There is scope of more work to understand how terroir affects the quality of the final product and how it can be communicated to the consumers, a practice which will also affect the marketing of Irish whiskey and will help it stand out against the competitors in the global market.

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The authors report there are no competing interests to declare.

11. Data availability Statement

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

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