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Multi-Criteria Analysis in Circular Economy Principles: Using AHP Model for Risk Assessment in Sustainable Whisky Production

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Abstract: As the whisky industry applies circular economy principles to maximize resource utilization and minimize environmental impact, companies become exposed to several risks, which require complex assessments to ensure reliable outcomes. This study provides an organized framework to identify, prioritize, and rank various risk factors commonly observed in the whisky industry through the development of an analytical hierarchy process (AHP) multi-criteria analysis model. Experts from 18 small European distilleries identified five main risk criteria and nineteen sub-criteria from brainstorming workplace observations and categorized them as: *environmental* (5), *operational* (4), *technological innovation* (3), *food safety* (3), and *economical* (4) risks. The analytical hierarchy process (AHP) approach was used to determine the weights and ranks of the main criteria and sub-criteria based on the survey responses received from experts from each distillery. The final judgements are consistent, as indicated by consistency values (CR) of less than 0.1 for all risk criteria. Unlike traditional risk assessment methods, the AHP model effectively integrates qualitative and quantitative data, aiding strategic decision making in the whisky industry by breaking down complex problems into manageable sub-problems. Future research directions may expand the criteria and explore additional sustainable practices.

Keywords: risk assessment; multi-criteria analysis; analytical hierarchy process (AHP); circular economy (CE); sustainable whisky production

1. Introduction

Circular economy (CE) is a shift from the traditional linear economy model, focusing on closed-loop systems where resources are reused, recycled, and regenerated [1–3]. The concept has gained considerable traction in recent years, with a growing body of literature exploring its application across various industries and niche markets [1]. The CE model minimizes waste and reduces environmental impact by extending the lifecycle of products and materials used [4–6]. When companies adopt sustainable practices and circular economy principles, risk assessment becomes essential for anticipating and preparing for uncertainties associated with these transitions [7,8]. Assessing risks associated with circular economy adoption, such as technological, financial, regulatory, and operational risks, allows companies to make informed decisions, allocate resources efficiently, and capture the full benefits of a circular model [6,9–14].

The ability of companies to engage in sustainable practices and implement circular economy principles is a key aspect of their dynamic capabilities [15]. Ref. [16] classifies dynamic abilities into three tiers: *incremental* (which focuses on consistent enhancement of the company's resources), *renewing* (which involves refining, adapting, and expanding resources), and *regenerative* (which requires a fundamental shift in the company's approach

to resource change) [15]. For instance, a risk assessment could identify potential risks in sourcing sustainable materials or transitioning to a circular supply chain, allowing the organization to develop strategies to mitigate these risks [17,18]. Several key studies highlight the benefits of circular economy practices, including cost savings, reduced environmental impact, and enhanced competitiveness [2,13,14].

In industries like food and beverage, integrating circular economy principles can reduce costs [19], increase sustainability [20], reduce food waste [21–23], improve resource efficiency [9,24], develop closed-loop supply chains [3,25] and meet consumer demands for eco-friendly products [25]. For example, breweries have implemented systems to recycle water and energy, while food manufacturers have developed methods to repurpose by-products into new products [26–28]. However, implementing circular economy practices at the micro-level poses challenges, as companies must overcome barriers like lack of infrastructure, high upfront costs, and resistance to change [6,10,14]. To address these barriers, risk assessment is crucial to identify potential risks and implement effective mitigation strategies [19,26,29].

The whisky industry, known for its rich heritage and traditional production methods, faces unique challenges in adopting sustainable practices due to its resource-intensive nature [4,15,28,30]. This highly fragmented and competitive market, with over 3500 independent whisky distilleries in 69 countries [31,32], was valued at USD 69 billion in 2023 and is projected to grow at a compound annual growth rate (CAGR) of 6.9%, reaching USD 123.65 billion by 2032 [28]. As the global demand for whisky continues to grow, the industry must find innovative ways to minimize its environmental footprint and embrace the principles of a circular economy [31,33–35]. Through the implementation of sustainable practices and the embrace of circular economy principles, the whisky industry can lead the way in demonstrating how traditional industries can adapt and thrive in a more environmentally conscious world. Recent trends show distilleries outside of the traditional whisky-producing countries are pioneering innovative techniques, utilizing unique ingredients, and challenging conventional norms [28], and creating new value chains can provide economic opportunities for the communities surrounding the whisky production facilities [30]. Managing by-products in a way that aligns with circular economy principles, such as repurposing spent grains as animal feed or bioenergy production, has significantly enhanced the industry's sustainability profile [21,36]. Biorefineries can also utilize whisky by-products and waste to create various fuels, chemicals, and materials [33].

This research paper explores the application of the analytical hierarchy process (AHP) model for risk assessment in whisky production, providing a framework for its implementation. The research aims to identify key risk factors from 18 European distilleries and develop a multi-criteria decision-making framework incorporating circular economy principles. By prioritizing these risks, whisky producers can better allocate resources, manage potential challenges, and develop effective strategies for sustainable production. Ultimately, this research seeks to contribute to the broader discourse on sustainability in the food and beverage industry, demonstrating the applicability of the AHP model in a practical, industry-specific context.

1.1. Sustainable Whisky Production

There are many challenges facing sustainable whisky production. They span across various stages of production, from ingredient sourcing to water usage, energy consumption, distillation, product aging, packaging, and the generation of by-products such as spent grains and pot ale.

Climate change challenges. Whisky character is significantly influenced by geographical location and climate [34]. An increase in global temperatures by 2 °C may result in yield losses of 46% for wheat and 31% for maize across the world, leading to supply chain disruptions and higher costs of raw materials [37]. Temperature control during malting and kilning is crucial, but high ambient air temperatures can cause overheating, while additional moisture reduces the effectiveness of fermentation [38]. Hot summer days can reduce

cooling efficiency, requiring additional water to prevent the fermentation from failing [37] or causing distillation to run slower and less frequently [39]. The aging process of whisky and oak is influenced by temperature and pressure, with warm temperatures accelerating maturation and altering the whisky character due to aggressive interaction [37].

Ingredient Sourcing and Agriculture. Whisky production relies on fertilizers and pesticides, causing soil and water pollution. To address these environmental challenges, the industry is shifting towards sustainable farming practices [34]. However, sourcing key grain ingredients like barley, corn, rye, and wheat can be challenging due to high water, land, and fertilizer requirements. Transitioning to organic or sustainably farmed grains can be costly and resource-intensive [10,40]. Organic barley can cost up to 50% more than conventionally grown barley [34]. Additionally, supply chain disruptions due to weather conditions, pests, or crop diseases can affect the availability, consistency, and price of barley and wheat crops [31,41,42].

Water usage. The whisky industry relies heavily on freshwater for various stages of production, including malting, mashing, distillation, and bottling [34]. Distilleries generally use their own private water source, thus contributing to the unique flavor of the finished product [37]. Water scarcity and droughts are known to force distilleries to halt production [34,38,42]. Approximately 61 billion liters of water are annually used, with a majority imputed in the cooling process. It is a water-intensive product, where the production of one liter of whiskey requires 46.9 L of water [42]. Considering both direct and indirect usage (e.g., water used for growing grains), the production of one liter of whiskey requires approximately 15,000 L of water [43]. Whisky production generates significant amounts of wastewater (20 L of wastewater to 1 L of whisky produced), which contains caustic soda, copper levels from copper stills, organic material, and other contaminants [34,37]. Companies meet environmental standards by implementing water management strategies, treating discharged water, increasing water consumption efficiency using the 3Rs principle (reduce, reuse, recycle), and performing water footprint assessments throughout product life cycles [4,26].

Energy Consumption. Traditional distillation, a highly energy-intensive process reliant on fossil fuels, significantly increases greenhouse gas emissions due to its heavy heat input. Just the Scotch whisky industry in Scotland, with only 175 distilleries, was reported to emit around 620,000 tonnes of CO_2 annually as of 2024 [34]. Significant upfront costs and technological advancements are needed to replace outdated equipment in the whisky production process or switch to renewable energy sources. Among the initiatives are increasing water conservation, employing renewable energy, and improving energy efficiency [4,15,30,34,36].

Waste management. Whisky production generates by-products like spent grains and pot ale, which can be repurposed for animal feed or compost [4,22,23,30,44,45]. For example, the Scotch whisky industry produces around 500,000 tons of spent grains annually [34]. Companies have implemented anaerobic digestion to convert organic waste into biogas, reducing CO_2 emissions by over 95% [4,28,43]. Ref. [34] reports that 90% of the industry's waste is now recycled or reused—a significant improvement from previous years.

Aging and Storage. The flavor of whisky is developed through years of aging in barrels, which presents unique sustainability challenges. The aging process requires large amounts of space and resources over many years, tying up significant capital and material. Whiskies are aged for various periods (minimum 3 years, and up to 30 years or more), making forecasts of demand in future periods subject to significant uncertainty [46,47].

Regulatory compliance. International production and safety standards, such as ISO 22000:2018—*Food Safety Management System* [48–50], FSSC 22000: Food Safety System Certification [48,51], ISO 45001:2018—*Occupational Health and Safety Management System* [52,53], ISO 14001:2015—*Environmental Management Systems* [54], and National Sanitation Laws are frequently adopted by whisky distilleries [30]. Production facilities are certified and run in accordance with international energy management system standards (ISO 50001) [55,56]. ISO 22000 integrates the principles of the *Hazard Analysis and Critical Control Points* (HACCP)

management system in which food safety is addressed through the analysis and control of biological, chemical, and physical hazards from raw material production, procurement, and handling, to manufacturing, distribution, and consumption of the finished product [50]. Additionally, ISO 31000:2018—*Risk Management—Guidelines* [57] and ISO 31010:2019—*Risk Management—Risk Assessment Techniques* [58] provide guidance on the selection and application of systematic techniques for risk assessment and risk management pertinent in the food and beverage industry [59].

The implementation of circular economy principles in the whisky production process entails a number of inherent risks that require careful consideration and analysis. Prior research has primarily focused on energy efficiency [36], water management [38], and waste valorization [22,30,44]. To identify, assess, and prioritize possible risks, risk assessment models like the life cycle assessment, failure mode and effects analysis, environmental risk assessment, and risk matrix are crucial for sustainable practices in the whisky production industry [59,60]. Few studies comprehensively evaluate sustainability risks in whiskey production [4,31,35,44,47]. The research aims to identify key risk factors from 18 European distilleries and develop a multi-criteria decision-making framework incorporating circular economy principles.

1.2. Analytical Hierarchy Process Model Used for Risk Assessment

One of the most crucial steps in the risk management process is accurately identifying potential sources of risk. Because risk criteria are determined based on an individual's perspective and experience, they are subjective. Using a multi-criteria analysis framework such as the analytical hierarchy process (AHP) model, which establishes the significance levels and consistency of the risk criteria, allows for a more objective risk assessment in complex settings for managing risk and uncertainty involving intuitive, rational, and even irrational aspects [61–63].

In risk assessment, the most widely used multi-scale decision-making technique is the analytical hierarchy process (AHP) [60–65]. Because of its adaptability, ease of computation, and integration with other strategies, it is the most popular and effective multi-criteria decision support method [61]. The method relies on the judgment of experts (trained members) who must use pairwise comparisons between items. AHP increases precision because it reduces the variability between experts in terms of the evaluated criteria [61,62,66]. This model lessens decision-making bias by utilizing the geometric average of each decision-maker's individual choice [61,66]. Thanks to AHP's consistency ratio, experts who deviate greatly from the group can be removed or retrained [62,67]. One of AHP's most significant benefits is its ability to prioritize criteria and sub-criteria in a well-balanced hierarchical structure [59,60,65]. Judgements are made between the criteria and the applicable alternatives using the 1-to-9 assessment scale, and comparison matrices are formed [66,68].

The AHP model has been applied in risk assessment in many industries, including construction, forestry, agriculture, logistics, and occupational health and safety [59,60,63,64,69–73]. Ref. [74] used the method to analyze food safety risk criteria in Baltic fish and the AHP method to rank these risk criteria in order of importance. As a result of the investigation, it was discovered that there were clear variations in the recognition and understanding of certain risk factors. Ref. [75], an AHP-based risk assessment model was created to assess the agriculture supply chain framework. Ref. [72] used AHP to rank the success factors in sustainable food supply chain management. In Ref. [73], fuzzy AHP and fuzzy TOPSIS were used to evaluate quality and sustainability in bakeries' production processes. The authors have previously used AHP to perform sensory analysis of buckwheat and sorghum beers [71]. However, there are no studies that we know of that evaluate risks in the field of sustainable whisky production using the AHP model.

Based on the above literature review demonstrating the whisky industry's shift toward circular economy practices with an emphasis on maximizing resource use and minimizing environmental impact, we formulated the following research hypothesis:

H1. *The AHP model will rank environmental risks as the most critical criterion for the whisky industry when adopting circular economy principles. Justification: Environmental risks, such as waste management, water usage, and carbon footprint, are likely to emerge as primary concerns.*

H2. *Food safety risks will have a high degree of consensus (CR < 0.05) across distilleries as a significant priority in risk assessment, regardless of size or location. Justification: Food safety is a critical issue in any consumable goods industry. In the whisky sector, consistency across small distilleries in viewing food safety as a low risk may be expected, reflected by strong consensus in the AHP model's outcomes.*

2. Materials and Methods

This study utilizes a combined qualitative and quantitative research methodology.

2.1. Qualitative Analysis—Identify Common Risk Factors from Case Studies

The qualitative analysis identifies key risk factors in whisky manufacturing through literature and interviews with micro-distilleries. Selecting appropriate evaluation criteria is crucial for the risk assessment's validity, with industry experts providing valuable insights from their practical experience. To make sure that the AHP model appropriately represents the company's priorities and the state of the industry, this expert input is crucial [66,68,76].

For the case studies, we chose to focus on whisky distilleries from continental Europe that were opened after 2000, which reduced the sample size to around 275 potential distilleries out of 580. Since European distilleries are mostly independently owned, very little information is available online. Our final case study pool consisted of 18 small distilleries that had a production capacity between 20,000 and 200,000 L (Table 1). Experts were selected from various areas of the whisky industry, including production, health and food safety, sustainability, regulatory affairs, and marketing, and were asked to brainstorm risks from workplace observations and work evaluations.

Table 1. Distilleries that participated in risk criteria brainstorming sessions.

| Country	Year Opened	Whisky Type (Grain Type)	Production (Liters)
Austria	2009	Single Malt Whisky (Barley)	~90,000
Belgium	2004	Single Malt Whisky (Barley)	~60,000
Czech Republic	2008	Single Malt Whisky (Barley)	~70,000
Estonia	2015	Single Malt Whisky (Barley)	~30,000
Finland	2014	Rye Whisky (Rye)	~100,000
France	2015	Malt Whisky (Barley), and Experimental (various grains)	~100,000
Germany	2016	Single Malt Whisky (Barley)	~200,000
Hungary	2002	Malt Whisky (Barley)	~30,000
Italy	2012	Malt Whisky (Barley), Rye Whisky	~90,000
Lithuania	2010	Grain Whisky (Rye, Wheat)	~50,000
Luxembourg	2004	Single Malt Whisky (Barley)	~20,000
Netherlands	2000	Single Malt Whisky (Barley), Rye Whisky, and Corn Whisky (Maize)	~150,000
Norway	2014	Single Malt Whisky (Barley)	~30,000
Poland	2005	Single Malt Whisky (Barley)	~50,000
Portugal	2018	Malt Whisky (Barley)	~20,000
Slovakia	2001	Grain Whisky (Corn, Wheat, Barley)	~100,000
Spain	2002	Malt Whisky (Barley)	~100,000
Switzerland	2005	Single Malt Whisky (Barley)	~100,000

2.2. Quantitative Analysis—Using AHP Model to Assess Risks in Whisky Industry

The analytical hierarchy process approach typically involves a hierarchical structure, pairwise comparisons, and a consistency evaluation to analyze complex decision-making

problems. In this study, the implemented AHP model utilized data collected from 18 European whisky production facilities to examine the factors influencing sustainable whisky production and the adoption of circular economy principles.

2.2.1. Step 1. Hierarchy Construction

As a result of the qualitative analysis, it was determined that whisky distilleries are commonly exposed to 19 risk sub-criteria within 5 main risk groups: *environmental* risks (5), *operational* risks (4), *technological innovation* risks (3), *food safety* risks (3), and *economical* risks (4) (Figure 1). Utilizing the analytical hierarchy process facilitates the examination of the importance and significance of each risk factor outlined in the hierarchical structure of Figure 1, thereby revealing how these risks influence the sustainability of whisky production. The primary purpose of this hierarchical approach is to simplify the complex problem and enhance overall understanding of the underlying factors impacting the sustainability of whisky production [61,68].
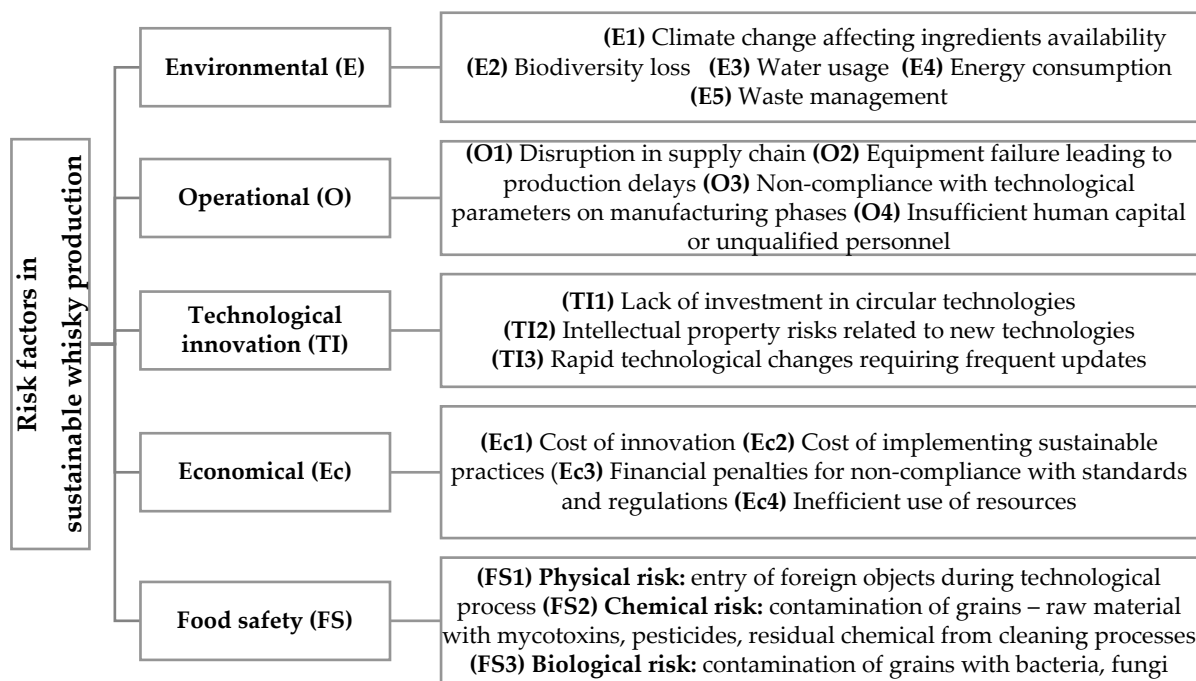
Figure 1. Hierarchical structure of risk factors in sustainable whisky production for a distillery.

A well-defined hierarchy ensures that the decision criteria and sub-criteria are appropriately decomposed, enhancing the model's accuracy and reliability [65]. The existing literature on analytical hierarchy process applications does not specify a strict minimum sample size requirement. Typically, AHP studies have been conducted with a range of four to fifteen decision-makers [61,62,71]. Furthermore, some studies have even included more than fifteen decision-makers in their AHP applications, demonstrating the flexibility of the method to accommodate a variety of sample sizes based on the research objectives and context [60,61,64].

2.2.2. Step 2. Pairwise Comparison

At this stage, the relative importance of the main criteria and sub-criteria is determined by comparing them in pairs, based on the judgment of the decision-maker. When comparing the criteria, the expert uses a pairwise comparison scale in Table 2 containing the numerical values between 1 and 9 determined by Refs. [66,68], where:

Table 2. Pairwise comparison scale for AHP preferences.

Intensity Scale	Definition
1	indicates equal importance
3	indicates moderate importance
5	indicates strong importance
7	indicates very strong importance
9	indicates extreme importance
2, 4, 6, 8	intermediate values between the two adjacent judgments.

Therefore, if the expert making the judgement considers a criterion to be strongly more important than another, it will receive a score of 5; and if it is less important, it receives a score of $\frac{1}{5}$.

For a given set of n elements (criteria or alternatives), the pairwise comparisons are represented in an $n \times n$ matrix $A = [a_{ij}]$, where:

$$a_{ij} = \frac{\text{relative importance of element } i \text{ to element } j}{\text{relative importance of element } j \text{ to element } i} = \frac{w_i}{w_j} \tag{1}$$

with $a_{ii} = 1$ for all i.

For instance, a pairwise comparison matrix A for three criteria might look like:

$$A = \begin{bmatrix} 1 & 3 & \frac{1}{5} \\ \frac{1}{3} & 1 & \frac{1}{7} \\ 5 & 7 & 1 \end{bmatrix}$$

where:

- $a_{12} = 3$ means that Criterion 1 is moderately more important than Criterion 2.
- $a_{21} = \frac{1}{3}$ means that Criterion 2 is less important than Criterion 1.

By aggregating the pairwise comparison matrices derived from the assessments provided by the whisky distillery experts using the geometric mean, a consolidated pairwise comparison matrix (A) is formed. This consolidated matrix can then be utilized to determine the significance or relative importance of each risk criterion under consideration. The resulting dimensional square matrix ($n \times n$) is formed by arranging the compared criteria in the corresponding rows and columns [66,68]. The matrices can also be represented as:

$$A = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \cdot & \cdot & \alpha_{1n} \\ \alpha_{21} & \alpha_{22} & \cdot & \cdot & \alpha_{2n} \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \alpha_{n1} & \alpha_{n2} & \cdot & \cdot & \alpha_{nn} \end{bmatrix} \tag{2}$$

where matrix A represents the pairwise comparisons of the criteria, and the dimension n corresponds to the number of criteria being evaluated.

When precise quantitative measurement is not feasible, it is essential to evaluate the consistency and reliability of the measurements. This is particularly important in cases where subjective assessments or expert judgments are used to determine the relative importance of different criteria or alternatives [66,76,77]. The characteristic function of a matrix, particularly in the context of a pairwise comparison matrix, is a key mathematical tool used to compute the eigenvector corresponding to the maximum eigenvalue:

$$f(\lambda) = |A - \lambda I| = \begin{bmatrix} \alpha^{11} - \lambda & \alpha_{12} & \cdot & \cdot & \alpha_{1n} \\ \alpha_{21} & \alpha^{22} - \lambda & \cdot & \cdot & \alpha_{2n} \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \alpha_{n1} & \alpha_{n2} & \cdot & \cdot & \alpha_{nn} - \lambda \end{bmatrix} \tag{3}$$

The eigenvectors of the matrix $A(\lambda_i)$ are calculated as follows:

$$f(A - \lambda_i)w_i = 0 \tag{4}$$

where w represents the eigenvector. Thus, the eigenvector corresponding to the maximum eigenvalue $(\lambda_{\max})$ is derived [40,41].

$$Aw = \lambda_{\max}w \tag{5}$$

Various methods are used to determine the eigenvector and eigenvalue in analytical hierarchy process research. In this study, the eigenvector and eigenvalue were calculated using the methodology outlined in Ref. [66]. To prevent excessively large or small values in the comparison matrix from causing issues with this approach, matrix A is normalized. This is achieved by dividing each value in the comparison matrix by the sum of the column elements, resulting in the elements of the normalized pairwise comparison matrix. The normalized element b_{ij} is calculated as:

$$b_{ij} = \frac{a_{ij}}{\sum\limits_{i=1}^{n} a_{ij}} \tag{6}$$

Matrix normalization facilitates the calculations and enhances the comprehensibility of the value comparisons since all values are standardized within the range (0, 1) [61,66,70]. To ensure that the results are consistent and can be readily interpreted, the elements of the eigenvector associated with the maximum eigenvalue are determined by calculating the average of the row elements in the normalized matrix A, as follows:

$$w_i = \frac{\sum\limits_{j=1}^{n} b_{ij}}{n} \tag{7}$$

Maximum eigenvalue $(\lambda_{\max})$ is calculated as:

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^{n} \frac{(Aw)_i}{w_i} \tag{8}$$

This approach generates reliable outcomes when there is substantial consistency in paired comparisons. The result represents an estimated value, and the more consistent the experts' assessments, the more precise the outcome will be. If the comparison results are unsatisfactory, decision-makers must revisit and refine the paired comparison process to ensure the integrity and accuracy of the risk assessment, which is crucial for enabling the successful implementation of circular economy strategies [64,66].

2.2.3. Step 3. Checking the Consistency Ratio

Human judgments are often subject to inconsistencies. Checking the consistency of these judgments is crucial to ensure that the derived priorities or weights are meaningful and reliable. Thomas Saaty, the creator of this method, defined the consistency ratio as the ratio of consistency index to random index [66,68]. The random index presented in Table 3 is calculated based on the number of criteria.

Table 3. Average random consistency index [61].

Size of Matrix (n)	1	2	3	4	5	6	7	8	9	10
Random Average CI (RI)	0	0	0.52	0.89	1.11	1.24	1.35	1.40	1.45	1.49

The random index depends on the size of the matrix. For n = 1 or n = 2, the RI is 0 because a matrix of size 1 or 2 is always consistent. As the matrix size increases, the RI values increase because the chances of inconsistency grow with more criteria.

The consistency index, which determines the acceptability of the consistency ratio for the comparison matrix A, is then calculated as [66,68,76]:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{9}$$

The consistency index (CI) represents the average degree of inconsistency in the matrix based on the characteristic equation's remaining solutions (see Table 3 for details). To evaluate and reduce inconsistencies in the comparison matrix, the consistency ratio (CR) is calculated using the formula from Refs. [66,68,76].

$$CR = \frac{CI}{\text{RandomaverageCI}} = \frac{CI}{RI} \tag{10}$$

where RI (random index) is a predefined value that varies according to the size of the matrix.

The consistency ratio (CR) indicates how consistent the expert judgments are. A CR value of 0.10 or less is considered acceptable, meaning the level of inconsistency in the comparisons is within an acceptable range [68,76].

3. Results

The study involved 36 experts from 18 whisky distilleries who were asked to evaluate and rate the risk criteria in the hierarchy on a scale of one to nine, based on their expertise and experience. These experts assessed the various risk factors associated with the circular economy model, such as supply chain disruptions, resource availability, and environmental compliance. The final comparison matrix for the main risk criteria was then constructed by calculating the geometric means of the data collected from these experts. The appropriate mathematical equation was used to generate the resulting matrix, which provided a comprehensive risk assessment framework for the circular economy.

According to Equation (1) the following matrix was formed:

$$A = \begin{bmatrix} 1 & 2.688 & 5.5 & 6.301 & 8.406 \\ 0.396 & 1 & 2.565 & 4.5 & 6.156 \\ 0.215 & 0.411 & 1 & 3.635 & 3.750 \\ 0.173 & 0.237 & 0.326 & 1 & 2.188 \\ 0.120 & 0.174 & 0.204 & 0.401 & 1 \end{bmatrix}$$

To create the pairwise comparison matrix normalized according to Equation (6), each element a_{ij} from matrix A was divided by the sum of the elements in the corresponding column. The following normalized pairwise comparison matrix was obtained:

$$A = \begin{bmatrix} 0.5254 & 0.5960 & 0.5731 & 0.3978 & 0.3900 \\ 0.2079 & 0.2217 & 0.2673 & 0.2842 & 0.2863 \\ 0.1129 & 0.0911 & 0.1042 & 0.2295 & 0.1744 \\ 0.0908 & 0.0525 & 0.0340 & 0.0631 & 0.1013 \\ 0.0630 & 0.0386 & 0.0213 & 0.0253 & 0.0465 \end{bmatrix}$$

The weight coefficients and consistency ratios of the main criteria were calculated by averaging the row elements of the normalized matrix A, according to the principle of Equations (7) and (9). As shown in Figure 2, the key risk criteria were identified as environmental risk (0.369), operational risk (0.253), technological innovation risk (0.181), economical risk (0.101), and food safety risk (0.096), based on their relative priorities. This finding aligns with the conclusions of a similar prior study, which emphasizes the

importance of considering these risk factors for ensuring the long-term viability and minimizing the negative environmental impacts of a circular economy.
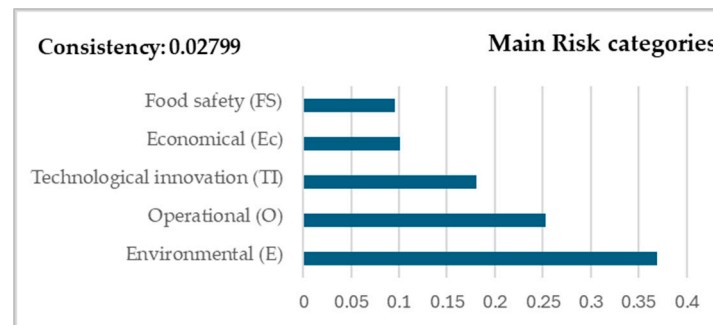
Figure 2. Priority ranking of main risk categories.

A priority weight of 0.369 suggests that *environmental* risk accounts for approximately 37% of the total importance assigned to all criteria. This high weighting reflects the emphasis placed on mitigating environmental impacts, particularly in contexts where sustainability and environmental stewardship are paramount, such as in a circular economy. Following at 25%, *operational* risk is critical in ensuring that the day-to-day functions of an organization or system are managed efficiently and that potential disruptions are minimized. The results show a moderate level of concern regarding the risks associated with the adoption of new technologies and innovations for the distilleries opened after the 2000s. *Economic* and *food safety* risks are perceived as less significant within the given context for European whisky distilleries.

The maximum eigenvalue (λ_{max} = 5.126) calculated from Equation (9) was placed in Equation (10), and the consistency index value (CI = 0.031) was calculated. The random index value given for the 5 parameters from Table 3 was taken as (RI = 1.11); the CI and RI values were placed in the relevant positions in Equation (10) and calculated: (CR = 0.028). Since the consistency ratio was less than the 10% limit value (CR = 0.028 < 0.1), it was decided that the comparisons of the experts were deemed consistent.

The same procedure was applied to determine the prioritization and weight of sub-criteria on each main risk category. As seen in Figure 3:

(a)	The sub-criteria with the highest *environmental* risk were determined to be climate change affecting ingredient availability (0.558), and water usage (0.186), while the lowest environmental risk was biodiversity risk (0.041). Waste management (0.116) and energy consumption (0.098) are very closely ranked. These findings explain the extensive focus in research literature on developing new technological alternatives that mitigate these risks. The CR value of 0.074 (the highest among other risk categories results from this study) implies that the prioritization may change, depending on the unique context under which certain distilleries may operate.

(b)	In the *operational* risk class, supply chain disruption (0.507) is perceived to hold the highest impact towards sustainable whisky production, followed by equipment failure leading to production delays (0.263) and non-compliance with technological parameters during manufacturing phases (0.152). Based on the experts' experience, unqualified personnel (0.078) had the lowest perceived contribution to operational risk. The consistency ratio CR of 0.004 indicates excellent consensus on the impact and priority of the sub-risks that were assessed.

(c)	The weights of the sub-criteria in the *technological innovation* risk category have been determined to be frequent technological updates (0.591) and intellectual property risks related to new technologies (0.333). Since the distilleries that participated in this study were built after the 2000s, the majority of them rely on newer technology and adhere to ISO guidelines. Therefore, the sub-risk lack of investment in circular technologies (0.075) is ranked relatively low for the selected target group. However, there are many frequent technological advances that can be adopted to address water

usage, waste management, and other environmental risks. The intellectual property implications of such solutions are often the driving factors of successful marketing strategies that satisfy customer preferences for reduced carbon footprint technologies, increase brand awareness of being sustainable, and help distilleries gain competitive advantage. The consistency ratio CR of 0.014 indicates consensus on the impact and priority of the sub-risks that were assessed.

(d)   In the *economic* risk class, inefficient use of resources (0.461) is by far the most important sub-criteria impacting sustainable whisky production, closely followed by the cost of implementing sustainable practices (0.305) and financial penalties for non-compliance with standards and regulations (0.187). The cost of innovation (0.046) is ranked lower than other economic sub-criteria since the sample population has less of an innovation and technological gap to address compared to traditional whisky distilleries that, for example, would need to buy equipment to modernize their production facilities. The consistency ratio CR of 0.016 indicates consensus on the impact and priority of the sub-risks that were assessed.

(e)   The main *food safety* risks associated with sustainable whisky production are chemical risks (0.671) such as contamination of grains—raw material with mycotoxins, pesticides, residual chemicals, from cleaning processes—followed by physical risks (0.265)—entry of foreign objects during technological process and biological risks (0.063)—contamination of grains with bacteria, fungi, etc. Biological risk has the lowest weight because of the nature of alcoholic beverage production, as the pathogenic microorganisms cannot survive the high alcohol content (min. 40% alc. vol.) present in whiskies. The consistency ratio CR of 0.030 indicates consensus on the impact and priority of the sub-risks that were assessed.
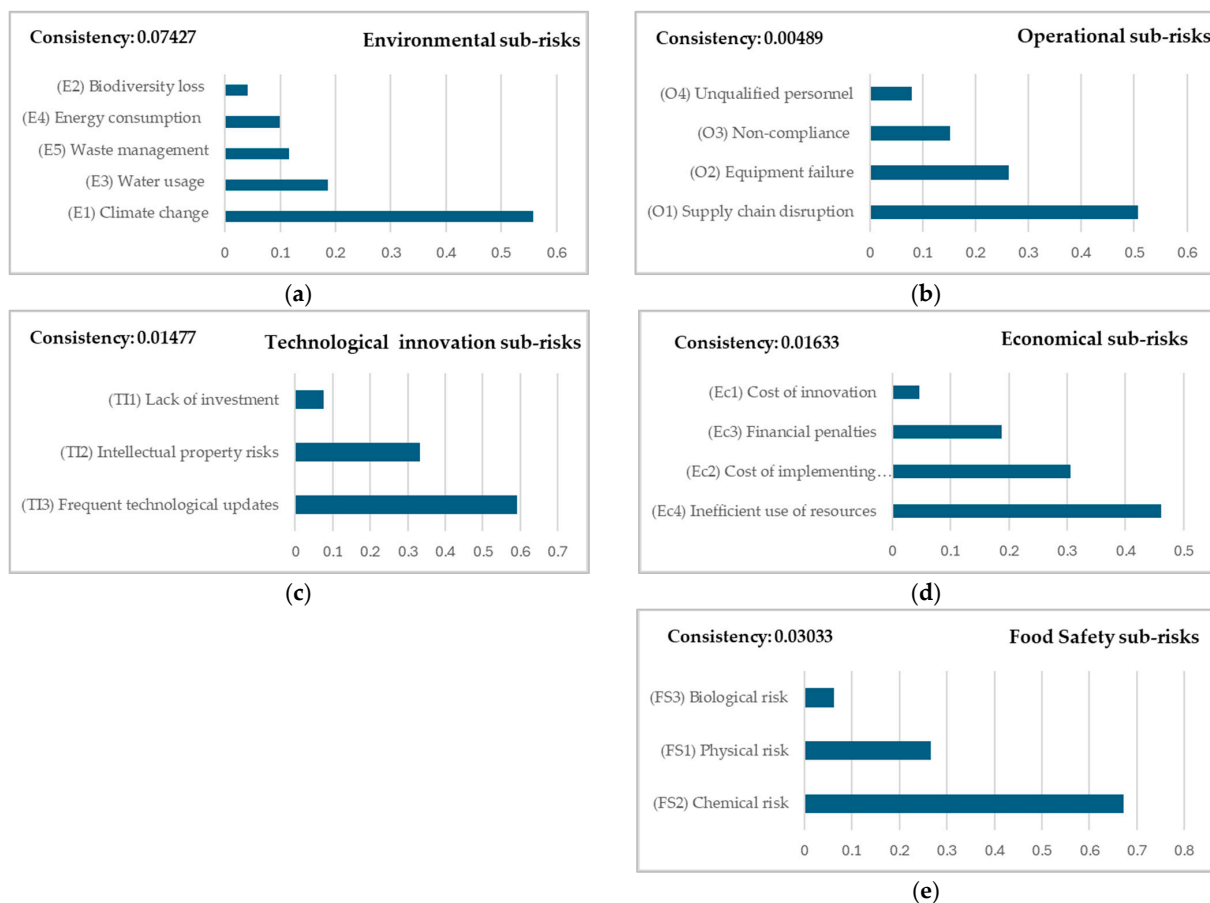
Figure 3. Priority ranking under each sub-criteria: (**a**) environmental sub-risks; (**b**) operational sub-risks; (**c**) technological innovation sub-risks; (**d**) economical sub-risks; (**e**) food safety sub-risks.

By comparing all sub-risks associated with each risk factor in pairs, the local weight (LW) coefficients for each sub-criterion were found, which allowed for the determination of the significance order of each sub-criterion. The calculation of global weight (GW) involved multiplying the local weight (LW) of each sub-risk by the relevant main risk criterion's local weight [61]. To ascertain the importance ranks of the sub-criteria shown in Table 4, the global weight values of each sub-criteria were listed.

Table 4. Weights and ranks of criteria and sub-criteria.

Main Risk	Local Weight (LW)	Sub-Criteria	Local Weight (LW)	Global Weight (GW)	Rank
Environmental (E)	0.369	(E1) Climate change [1]	0.558	0.247	1
		(E2) Biodiversity loss	0.041	0.018	13
		(E3) Water usage	0.186	0.082	4
		(E4) Energy consumption	0.098	0.044	8
		(E5) Waste management	0.116	0.051	7
Operational (O)	0.253	(O1) Supply chain disruption	0.507	0.139	2
		(O2) Equipment failure [2]	0.263	0.072	5
		(O3) Non-compliance [3]	0.152	0.041	9
		(O4) Unqualified personnel	0.078	0.021	12
Technological innovation (TI)	0.181	(TI1) Lack of investment [4]	0.075	0.015	15
		(TI2) Intellectual property risks [5]	0.333	0.065	6
		(TI3) Frequent technological updates	0.592	0.115	3
Economical (Ec)	0.101	(Ec1) Cost of innovation	0.047	0.003	18
		(Ec2) Cost of implementing sustainable practices	0.305	0.017	14
		(Ec3) Financial penalties [6]	0.187	0.010	16
		(Ec4) Inefficient use of resources	0.461	0.025	10
Food safety (FS)	0.096	(FS1) Physical risk [7]	0.265	0.009	17
		(FS2) Chemical risk [8]	0.672	0.023	11
		(FS3) Biological risk [9]	0.063	0.002	19

[1] climate change affecting ingredients availability; [2] equipment failure leading to production delays; [3] non-compliance with technological parameters during manufacturing phases; [4] lack of investment in circular technologies; [5] intellectual property risks related to new technologies; [6] financial penalties for non-compliance with standards and regulations; [7] physical risk: entry of foreign objects during technological process; [8] chemical risk: contamination of grains—raw material with mycotoxins, pesticides, residual chemical from cleaning processes; [9] biological risk: contamination of grains with bacteria and fungi.

As seen in Table 4 above, the five most important sub-risk criteria that new whisky distilleries are exposed to are: climate change affecting ingredient availability, supply chain disruptions, frequent technological updates, water usage, and equipment failure leading to production delays.

To prioritize the sub-risk criteria within the main risk criteria, the λ_{max}, CI and CR values of each main risk criteria class were calculated in separate AHP applications. The consistency was assessed by comparing the CR value with the limit value of 0.1 (Table 5 below). Since all risk criteria had CR values less than 0.1, the decisions made for each expert were consistent.

Table 5. λ_{max}, CI, and CR values of main criteria according to AHP analysis.

Main Risk Categories	λ_{max}	CI	CR	Decision (CR $\leq$ 0.1)
Environmental (E)	5.334081	0.083520	0.074270	Consistent
Operational (O)	4.013335	0.004445	0.004888	Consistent
Technological innovation (TI)	3.014153	0.007077	0.014767	Consistent
Economical (Ec)	4.044563	0.014854	0.016333	Consistent
Food safety (FS)	3.029071	0.014536	0.030330	Consistent

4. Discussion

The application of the analytical hierarchy process model in this study provides a structured and insightful examination of the risk landscape for new whisky distilleries established in Europe after the 2000s. The results underscore the significance of systematically prioritizing risks to enhance sustainable production and operational efficiency. Circular economy principles emphasize the importance of resource efficiency, waste reduction, and sustainable practices across all sectors. The study's findings have several notable implications that align with and expand upon existing research, offering new perspectives on risk management in the whisky distillery industry.

The results of the study confirm Hypothesis H1, which posited that environmental risks would be ranked as the most critical criterion in the whisky industry when adopting circular economy principles. The AHP model revealed that *environmental risks* hold the highest weight coefficient (0.369), underscoring their importance relative to other risk categories. This result is consistent with the larger body of research on sustainability in the beverage sector, where environmental issues like waste management, water use, and climate change are increasingly recognized as major obstacles. Climate change's impact on ingredient availability is prioritized at 0.558, indicating a growing understanding of the direct effects that these changes can have on the supply chain and ingredient quality. This result is in line with earlier research that highlights how susceptible agricultural inputs are to climatic variability and emphasizes the necessity of creative risk-reduction tactics. Furthermore, the focus on waste management and water use draws attention to persistent worries about resource efficiency, a recurring theme in sustainability research. According to these findings, distilleries should put an emphasis on environmental stewardship and implement cutting-edge technologies to effectively reduce these risks. By doing so, they will be able to meet consumer demand for environmentally friendly products and global sustainability goals.

Operational risks are the second most important risk category (0.253), with the most important sub-risks being supply chain disruptions (0.507) and equipment failure (0.263). These results validate earlier studies that show equipment reliability and supply chain resilience as essential components for continuous production in manufacturing industries. With the recent global supply chain challenges brought on by the COVID-19 pandemic, it is especially noteworthy that supply chain disruptions have been given such high priority. This indicates that in order to minimize any disruptions, new distilleries should invest in strong supply chain management plans and backup plans. Furthermore, research emphasizing the value of maintaining operational continuity and minimizing downtime to maximize production efficiency and cut costs is consistent with the focus on equipment failure. Expert agreement, as demonstrated by the low consistency ratio (CR = 0.004), further supports the validity of these results and points to a broad consensus regarding the operational difficulties distilleries face.

Significant weights assigned to frequent technological updates (0.591) and intellectual property risks (0.333) highlight the importance of *technological innovation* risks (0.181). The swift advancement of technology and the requirement for distilleries to consistently innovate to stay ahead of the competition are both reflected in this finding. Since many new distilleries rely on contemporary machinery and technologies, it is suggested that keeping up with technological developments should be a top priority due to the emphasis on frequent updates. This is especially important given how the whisky industry is going digital, automated, and using data analytics. Innovations that give a competitive advantage must be protected, as the significance of intellectual property risks emphasizes. These observations are consistent with the body of knowledge regarding the contribution of technological innovation to improved market differentiation and operational efficiency [29]. While sustainability is a priority, the weight given to the lack of investment in circular technologies (0.075) is relatively low, suggesting that the immediate focus is still on utilizing current technological capabilities rather than making significant investments in new circular technologies.

The study also identifies significant *economic* risks (0.101) as a notable concern, especially in relation to resource waste (0.461) and the expense of adopting sustainable practices (0.305). These results are in line with earlier studies that have highlighted the financial difficulties in implementing sustainable practices, particularly for new players in the market who might have severe funding shortages. Given the high ranking of inefficient resource use, distilleries should concentrate on streamlining their processes to reduce waste and increase resource efficiency, as this is essential to preserving their competitiveness and cost-effectiveness. This outcome is also consistent with more general economic trends, which call for striking a balance between sustainability and financial viability. Experts generally agree on these economic issues, as evidenced by the consistency ratio (CR = 0.016), which highlights the necessity for distilleries to develop cost-effective sustainability strategies.

Lastly, the risks to food safety (0.096) are emphasized, with the most important sub-risk being chemical risks (0.671), which include contamination from pesticides and mycotoxins. This research emphasizes how crucial it is to uphold strict food safety regulations in the whisky industry, especially as consumers grow more conscious of these concerns. The natural antimicrobial qualities of alcohol, which lessen the possibility of bacterial contamination, are consistent with the lower ranking of biological risks (0.063). These findings are consistent with earlier research emphasizing the need for strict quality control procedures to avoid contamination and guarantee product safety. The industry's recognition of the significance of food safety is reflected in the moderate consistency ratio (CR = 0.030), which indicates a reasonable level of agreement among experts. The research confirms Hypothesis H2, which suggested a high degree of consensus across distilleries regarding the low prioritization of food safety risks.

The study assesses commonly found risks for new whisky distilleries in Europe, emphasizing environmental sustainability, operational resilience, technological innovation, economic efficiency, and food safety. It contributes to sustainable practices and offers insights for future research, using the AHP model for decision making.

4.1. Limitations of the AHP Research

The AHP model used in a study for decision making in new distilleries in Europe has several limitations, including potential expert bias and subjectivity, inability to fully capture the dynamic nature of the industry, limited scope of risk factors considered, and limited applicability to distilleries in other regions or time periods. The study focuses on a predefined set of main risk categories and sub-criteria, potentially overlooking other relevant factors that could impact new distilleries. For example, social and cultural factors, brand reputation, or market competition might also play a significant role but were not included in the analysis. Additionally, the model assumes a static decision environment, which may not accurately reflect the evolving market conditions, technological advancements, and regulatory landscapes. The conclusions may not apply directly to older distilleries or those in other regions with different operating environments and regulatory requirements because they are specific to new distilleries in Europe built after the 2000s.

4.2. Recommendations for Future Research

To address these limitations and build on the current findings, future research should expand the AHP model's scope to include social factors, market dynamics, and brand-related risks to better understand the challenges faced by distilleries. Longitudinal studies could track changes in risk priorities over time, while integrating AHP with other decision-making models and risk assessment models could improve its ability to handle interdependencies. Expanding the geographic scope could provide a global perspective on risks in the whisky industry. Exploring the impact of emerging technologies like artificial intelligence, blockchain, and the Internet of Things (IoT) on risk management could provide valuable insights. Additionally, conducting case studies at specific distilleries could further validate the model's applicability in real-world settings.

By addressing these areas, future research can further refine the AHP model, enhance its applicability, and provide valuable guidance for new distilleries navigating the complex landscape of risk management.

5. Conclusions

This study shows how the analytical hierarchy process (AHP) model can be used effectively to assess risks in the production of sustainable whisky, especially when distilleries implement the circular economy. The AHP model offers a strong framework for determining, ranking, and prioritizing the different risk factors that new whisky distilleries in Europe must contend with by combining qualitative and quantitative data. Thirteen sub-criteria and five primary risk criteria—environmental, operational, technological innovation, economic, and food safety risks—were identified by the analysis, which involved thirty-six experts from eighteen small European distilleries. The findings show that operational risks like supply chain disruptions and technological innovation risks, such as the requirement for frequent technological advancements, are second most important for sustainable whisky production, after environmental risks, particularly those pertaining to climate change and water usage.

The results emphasize how critical it is to approach risk management methodically in a way that is consistent with sustainable practices and the ideas of the circular economy. The AHP model's reliability is validated in this context by the experts' consistent judgments, as evidenced by the low consistency ratios (CR < 0.1) across all risk categories. By offering a thorough framework for risk assessment, the study adds to the larger conversation on sustainability in the food and beverage sector. This framework can help whisky producers make more informed strategic decisions and improve their ability to effectively manage risks.

The study acknowledges limitations in its application of the AHP model, including reliance on expert judgments and its static nature. Future research should include social, cultural, and market dynamics, longitudinal studies, and the impact of emerging technologies on risk management. This will enhance the applicability of the model and offer valuable insights for sustainable whisky production and risk management.

Author Contributions: Conceptualization, D.D. and A.C.; methodology, D.D. and A.D.; software, D.D.; validation, A.C., A.D. and C.-E.N.; formal analysis, D.D. and A.C.; investigation, D.D.; resources, D.D.; data curation, D.D.; writing—original draft preparation, D.D.; writing—review and editing, A.C., C.-E.N. and A.D.; visualization, D.D.; supervision, C.-E.N. and A.D. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement: Data are contained within the article.

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

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