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Worldwide Illicit and Counterfeit Alcoholic Spirits: Problem, Detection, and Prevention

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ABSTRACT
Worldwide, counterfeit, illicit, and untaxed alcoholic spirits are responsible for problems with economy, labor, and public health. Estimations of counterfeit spirits range from 25% to 40% of total alcoholic spirits consumed globally. Including knock-on effects, these products cost the EU alone €23,400 lost jobs and at least €38 billion in lost revenue per year. Annually there is at least €1.2 billion in lost government revenue. Counterfeit products decrease legitimate sales, both by replacement sales, and by the erosion of consumer product trust and satisfaction of legitimate goods and decrease legitimate manufacturing jobs. We review the worldwide problem, scope, and scale of the spirits counterfeiting problem including specific health issues, and the international plight of reduced labor available resulting directly from production and sale of counterfeit liquor. In addition, we review a wide range of methods and technologies to analytically detect chemically adulterated or substituted products that have been published and group technologies into 4 functional areas highlighting economy, generality, and utility. Approaches to prevention are also discussed.

KEYWORDS
Authenticity; counterfeit; illicit; poisoning; spirit analysis

Introduction
Illicit, undocumented, and counterfeit spirits damage human health, economy on global and local scales, and damage consumer confidence in otherwise strong brands. Piracy and counterfeiting, defined broadly, are the unauthorized rebranding and manufacture of a consumer product under a false premise. These crimes in total were estimated to be almost a half-trillion USD as of 2016. Illicit and counterfeit spirits are one component of the worldwide problem in counterfeit consumer goods. These illicit spirits are significant problems both from an economic and a health standpoint. Specifically, each year thousands of deaths and injuries are reported from ingesting toxic and poisonous compounds that were presented as spirits.

In the case of distilled spirits, while frequently called counterfeit, that name is subjective and any instance where the product is not exactly what is claimed can be called illicit or counterfeit. This can be through dilution of original product with lesser quality or less expensive product, or generally the replacement of one bottled spirit with a different spirit in the original bottle. Additionally, the manufacturing and sale of illicit spirit can be very profitable, and the penalties are typically less, and the risk less, than for crimes such as narcotics manufacture. From a cost-benefit perspective, illicit spirits can be safer, more lucrative, and because it is perceived as a less substantial offense often with lesser penalties, more attractive for criminals to produce.

There is no one type of illegal spirits. They can be improperly labeled actual spirit, with information intended to deceive the consumer. As such, exact amounts of illicit spirit consumed are not known. The World Health Organization (WHO) estimates that at least 25% of all spirits are illicit while many other authorities including the United Nations Conference on Trade and Development (UNCTAD) Illicit Trade Forum state over 40% in some areas. It has been shown analytically that as much as 33% of tested old and collected Scotch whisky is counterfeit. In 2018, the Scottish Universities Environmental Research Centre (SUERC) tested 55 bottles of Scotch Whisky that were old and considered rare, that were obtained from private collectors, auctions, and retail. Of these, 21 (38%) were counterfeit. Further in the same study, all spirits in the test from before 1900 were not authentic.

However, counterfeit spirits are not always a deception against the consumer. There are instances where the consumer desires a lower priced product and knowingly purchases illicit products. The oftentimes cheaper purchase price is frequently all that is required to compel consumers to purchase knowingly illicit spirit.

While legitimate distilled spirits are primarily ethanol and water, with compounds naturally derived from fermentation as well as aging, other naturally derived compounds are frequently found. These compounds depend on the category of distilled spirit but include volatile compounds such as monocarboxylic acids and their esters, aliphatic carbonyl...
Counterfeit or illicit spirit can also include the above compounds if derived from legitimate operations, but lesser quality product can contain many poisonous compounds including nail polish remover, methanol, and paint stripper. Other compounds that can be found in counterfeit spirit include chemicals used in cleaning fluids, car window wash, antifreeze and some fuels, ethyl acetate (normally found in glues), and acetaldehyde (compound used in industrial processes and which can occur naturally in alcoholic beverages but is potentially cancerous if concentrated).

**Description of problem**

When we refer to illicit spirits generally, it can have several embodiments. There are several generally accepted definitions of counterfeit or illicit spirit:

- a. Surrogate alcohol, specifically industrial rectified alcohol (ethanol) used in addition to or in place of what consumers expect to purchase. The rectified ethanol is typically mixed with water and other ingredients including color and flavor to complete the deception.
- b. Product replacement - a known good product is replaced with a similar product of lesser value. For instance, the reclamation of used bottles that are sealed and sold as new. This simplifies the process, and no fundamental organoleptic correction is required as the flavor and color are presumably similar. In addition, this is a ‘safes’ method to produce or obtain illicit spirit because one starts with known good product, albeit at a lesser price.
- c. Industrial rectified alcohol (ethanol) mixed with methanol. Methanol is included because it has similar intoxicating effects to ethanol and is significantly less expensive.
- d. Industrial methylated (denatured) alcohol. This has had methanol added (and other compounds such as bittering agents) to allow the sale of predominately industrial ethanol with no tax such as that associated with potable spirits. The bittering agents and dyes are often chemically removed.
- e. Bottle reuse wherein existing authentic packaging is refilled with lesser quality spirit, resealed, and sold as original.
- f. Legitimate distillers provide the spirit and either mislabel on site or provide spirit to others who will fill and mislabel bottles of spirit, often with labels of more expensive or older products.
- g. Tax leak product where the spirits are produced legally but they are distributed in a fashion that there is no tax or lower tax paid, which can include cross-border transportation – from areas of different value added tax (VAT).
- h. Substitution of product where industrial rectified spirit has been redirected to the spirits drinks market.
- i. Contraband product where the importation is arranged such that the correct duty has not been paid.
- j. Complete counterfeiting, where the product is not legitimate and the bottles, labels, and closures are not authentic. In addition to the stated problems, this type of spirit can also have, in addition to methanol, high levels of lead, mercury, and other contaminants simply from the improvised distilling equipment used.

In this paper we will reserve counterfeit as a distinction uniquely for product that is sold via deception, where the consumer believes they are purchasing a known consumer product and yet are purchasing usually inferior product. Illicit product will refer to the totality of non-authentic product including all non-taxed, illicit, and counterfeit product.

The Alliance Against Counterfeit Spirits (AACS) is a worldwide organization committed to fighting against counterfeit spirit products. They have trained almost 17,000 law enforcement agents and have been responsible for the confiscation of over 4 million bottles of counterfeit liquor. The AACS list 5 areas where counterfeit spirits damage society:

1. **Poisons in consumable products**: this includes packaging for drink compounds including methanol, cleaning fluids, nail polish remover, automobile window wash, and isopropanol.
2. **Increased crime**: intellectual property piracy puts more money into the hands of criminals, strengthening that enterprise. The Business Action to Stop Counterfeiting and Piracy (BASCAP) estimates all intellectual property (IP) crimes inject $60B USD per annum into criminal enterprises.
3. **Counterfeiting hurts direct foreign investment**: Countries that have poor control on IP rights will have reduced foreign investment. Worldwide it is estimated that direct foreign investment is reduced by $111B USD annually because of decreased investment in countries that have poor or poorly perceived rule of law covering intellectual property.
4. **Genuine economic impact**: a consumer who knowingly purchases a counterfeit product is much less likely to purchase a genuine equivalent product. Producers are robbed of that revenue.
5. **Less public money and taxes**: as a result of the decreased tax generated from counterfeit consumption, there is less public money for those areas that are socially included such as schools and roads.

The AACS state that other actions contribute to counterfeiting enterprises including bottle reuse, online sales of empty used bottles, and specialized suppliers who facilitate or enable counterfeiting by making dry products (labels and caps), as well as the wet products (flavors and rectified spirit).
Economic issues due to illicit spirits production

The amount of money removed from the normal commerce stream due to counterfeit spirit is daunting. The single category of whisky sales has a worldwide value of approximately $88B USD in 2023. Published values from 25 to 40% counterfeit imply that between $22B USD and $35.2B USD is diverted from its intended recipients.

The US Alcohol Tobacco and Firearms confiscation reports indicate that between 1990 and 1995 there were under 400 total gallons of illicit spirit seized and a total of two stills seized. Most of the entire nation’s effort was on one county – Franklin County Virginia. However, this does not accurately describe the magnitude of the counterfeiting problem, where it is estimated that a small number of distillers made over 1.5 million gallons of spirit and that the state and federal government lost approximately $20 M USD from unpaid taxes.

China has reported more counterfeit spirit seizures than any other country. In 2011, CCTV showed a single arrest of counterfeiters that stopped the sale of almost $500 M USD of illicit product. In 2020, 13 criminals were sent to jail for producing illicit Moutai. This group had over 27,000 bottles of product ready to sell.

In December of 2020, Spanish authorities confiscated over 300,000 counterfeit whisky bottles. Also in the same raid, authorities found 171,200 illegal tax stamps, and 27,000 boxes complete with logos. Had this been sold, the specific but unnamed brand of whiskey would have had over €3.8 M of damages through displacement of legitimate sales. Across the EU, the annual sales loss from counterfeit spirits is estimated as €3B, which translates to over €1.2B in lost government revenue, and over 23,400 lost jobs. Wider EU job losses are detailed in Table 1.

In the UK, from a study dated 2013, counterfeit spirits have an almost £1.5B economic impact from unpaid tax revenue. In 2009, 9000 bottles of a spirit product labeled Glen’s Vodka were confiscated. The criminals were an organized gang, and used chlorine bleach to remove denaturing additives and purple colorant from industrial alcohol. In addition to the bottles of finished product confiscated, authorities seized an additional 25,000 liters of pure methylated spirits and records to indicate that at least 165,000 bottles had been sold between 2008 and 2009.

Damage to local economies and business is also significant. For example, regarding the fallout from the significant number of tourists and citizens that were poisoned from methanol containing spirits in resorts and hotels in the Dominican Republic, in June of 2022, the director of Pro Consumidor, The National Institute for the Protection of Consumer Rights in the Dominican Republic stated that business that had been involved in the distribution of illicit beverages will never reopen.

It is often difficult to quantify the entire value of lost sales from product counterfeiting. The value of lost sales is determined primarily from confiscated product, however that is not a complete metric because only an unknown percentage of illicit product is confiscated. One common approximation involves determining the expected sales and increasing by the anticipated sales growth, for a specific category, during the period under observation. The difference between actual sales and sales projections, in this model, represent the amount of counterfeit product.

As detailed later, most illicit spirit detection technologies rely on expensive and cumbersome techniques that are invasive (requiring a physical sample to be removed from the bottle) and require expensive reagent chemicals and a highly trained operator, or a prohibitively expensive through the bottle detector. With no readily available direct tool for detection, various estimation models for total counterfeit spirits are employed. Estimation methods include statistical extrapolation models such as the Auto-Regressive Integrated Moving Average model (ARIMA).

A combination of intercepted counterfeit products and company failed sales projections are metrics to help gauge the quantity of illicit spirits that have entered the supply chain. While historically, ARIMA has been used with time series forecasting, it is also used for consumptive expenditure forecasting. This model begins with the historical consumption of a given product and then will forecast a future consumption. The forecasted predicted consumption model includes, in this case, decreased consumption of legitimate products due to counterfeit displacing legitimate goods, as well as external economic and social pressures and trends that will change national consumption. One value of the ARIMA model is the quantification of the relative error of the given prediction, which quantifies the difference between the forecasted consumption and the actual level of consumption.

As described above, broadly speaking, illicit spirits can fall into two areas: those spirits and packaging that are intended to deceive and those spirits and packaging that is intended to cost less. As a given population may transition from greater general prosperity to lower affluence from external social and political forces, it can shift counterfeiting from one of intent to deceive to one of simply providing lower cost products. Other factors that make the accurate forecast of legitimate spirits difficult is determining a consumption level with no counterfeiting, versus consumption impacted by counterfeiting.

In addition, in many markets there are complex and uncertain economic and social constraints, including those changes in individual disposable income due to economic and political stressors, the change to the national gross domestic production (GDP) and national GDP growth. Also, the exchange rate in the local currency as compared to

Table 1. European Union (including UK) lost jobs due to counterfeit spirits 2016–2017

<table>
<thead>
<tr>
<th>Sector of lost employment</th>
<th>Jobs lost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>8600</td>
</tr>
<tr>
<td>Food industry</td>
<td>6100</td>
</tr>
<tr>
<td>Wholesale trade</td>
<td>1200</td>
</tr>
<tr>
<td>Retail trade</td>
<td>700</td>
</tr>
<tr>
<td>Land transport</td>
<td>700</td>
</tr>
<tr>
<td>Security services</td>
<td>700</td>
</tr>
<tr>
<td>Investigation services</td>
<td>700</td>
</tr>
<tr>
<td>Legal service</td>
<td>500</td>
</tr>
<tr>
<td>Accounting</td>
<td>500</td>
</tr>
<tr>
<td>Employment services</td>
<td>500</td>
</tr>
</tbody>
</table>
global currencies can impact the tolerance for counterfeiting. Furthermore, there is the national consumption of spirits as influenced by social pressures, stressors and motivators, the current national appetite for spirit and the national attitude and outlook for a given period, and growth or contraction of population and shifting demographics based on age, income, and gender.[1] Over the last several decades, the global trend has been toward lower quantities of spirits consumption, which is an additional factor complicating the estimation of the impact of counterfeits on the overall economy.

The effects from counterfeit spirits are more significant than simply lost sales. Other economic implications, called knock-on effects, exacerbate financial shortcomings.[29] Losses include:

1. Lost sales and decreased revenue, from legitimate products displaced by duplicate counterfeit products.
2. Because less product is sold, fabricators or manufacturers require fewer employees since legitimate manufacturers do not expand production as readily.
3. Because there are fewer products, manufacturers make less money. Because less revenue is generated at a manufacturing facility, less taxes including VAT, household income tax, and corporate profits tax are collected because of lowered sales from legitimate manufacturing channels. It is not customary for criminals to pay tax on counterfeit products.
4. Fewer service companies and fabrication equipment are required, due to lessened production at legitimate manufacturing facilities.
5. Less industrial services purchased because of lower conventional production.
6. Less governmental contributions including social security, and other regional forms of social tax.
7. Less export and excise duty.

**Corporate risk from illicit spirits**

It is well accepted that counterfeit spirits are a significant business risk to distillers the world over. *Diageo*, in their 2022 annual report lists counterfeit spirits as a principal threat to their business, being as significant as product quality and macroeconomic volatility. They state counterfeit spirits is one of their 10 key areas for ‘effective risk management’. To address this, Diageo describes packaging based solutions, which makes bottle and label reuse more difficult. In addition, they put emphasis on the monitoring of social media to remove resold empty bottles or other counterfeit listings.[32] Brown-Forman, in their annual report list, in a scorecard format, the 9 most significant risks they anticipate, which includes "counterfeit and look-alike products damaging brand image and impacting sales". They state that "counterfeiting and inadequate protection of our intellecction property rights could adversely affect our business prospects” and that can influence their financial returns to differ materially from their statement.[10] Specifically, this is one of only five stated factors that would materially change their business in the coming year.

**Worldwide health problem from illicit spirits**

In addition to the economic and corporate reputation problems, there are profound health problems from counterfeit and illicit spirits toxic components and adulterants including but not limited to methanol, 2-propanol, and acetone. There are many instances of widespread individual and mass poisoning from illicit spirit. Both methanol and 2-propanol have intoxication somewhat like ethanol.[27] Table 2 gives a partial list of other toxic compounds found in illicit spirits.

It is important to point out that in many cases the consumer of counterfeit spirits do so willingly simply to spend less than would have been done purchasing legitimate spirits. Unfortunately, it seems those consumers are most often the victim of serious poisoning.[38] Table 3 gives a partial listing of various countries’ illicit spirits deaths. Examples of illicit spirit production subsequently resulting in consumer fatalities include:

**Estonia**

In Pärnu Estonia in 2001, 1.6 metric tons (10 × 200-liter canisters) of methanol was stolen from a company called Baltfett, which industrially processes animal feed, esters, and industrial fats. The original thief is presumed to have known that they had stolen methanol, however represented it as ‘laboratory grade neutral spirit” and the buyer did not know otherwise. The methanol and water mixture was bottled and labeled with brands that were known as legitimate spirits. From this 68 people died and at least 40 other people

<table>
<thead>
<tr>
<th>Compound</th>
<th>Location</th>
<th>Health consequence</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methanol</td>
<td>China, Russia, USA, UK, Brazil, Poland, more Lithuania</td>
<td>Blindness</td>
<td>[33]</td>
</tr>
<tr>
<td>Ethyl-phthalate and Carbamates</td>
<td>Lithuania</td>
<td>Carcinogen</td>
<td>[34]</td>
</tr>
<tr>
<td>Cyanide derivatives Carbamates</td>
<td>Brazil</td>
<td>CNS toxicity</td>
<td>[36]</td>
</tr>
<tr>
<td>Toxic metals</td>
<td>Brazil, China, Lithuania</td>
<td>Carcinogen</td>
<td>[35]</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td></td>
<td>Several health issues. Highly reactive and toxic</td>
<td>[37]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Country</th>
<th>Year</th>
<th>Deaths (hospitalizations)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cuba</td>
<td>2013</td>
<td>7 (41)</td>
<td>[39]</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>2012</td>
<td>38</td>
<td>[40,33]</td>
</tr>
<tr>
<td>Ecuador</td>
<td>2011</td>
<td>23</td>
<td>[41]</td>
</tr>
<tr>
<td>Kenya</td>
<td>2014</td>
<td>55</td>
<td>[42]</td>
</tr>
<tr>
<td>Kenya</td>
<td>2005</td>
<td>130</td>
<td>[42]</td>
</tr>
<tr>
<td>Libya</td>
<td>2013</td>
<td>101</td>
<td>[43]</td>
</tr>
<tr>
<td>Uganda</td>
<td>2010</td>
<td>80 (1066)</td>
<td>[44]</td>
</tr>
</tbody>
</table>
suffered permanent health problems including brain damage and blindness.\textsuperscript{[45]}

**Kenya**

In Nairobi, Kenya, in 2000, at least 140 people were killed and 400 were admitted into local hospitals as a result of a drink that had methanol added to increase the overall alcohol content. In 1999 there were at least 23 deaths and additional permanent physical damage from spirits adulterated with methanol. In 1998, a single event resulted in 100 deaths.\textsuperscript{[42]}

Kenya has a long tradition with a spirit that is called homebrew but represents various spirits. The distilling process is different depending on the village. The starting components can be bananas, grain, or coconut-based products. Though this is called homebrew, a name most often associated with beer, this is a distilled product that has been found to contain adulterants including methanol, battery acid or other higher alcohols. This product, though diverse in manufacturing, remains popular due in large part to its low price. One glass of a product called chang’aa, that can also be called “kill me quick” is as cheap as 10 cents US, which in turn is one tenth the cost of a low-cost beer.\textsuperscript{[42]} In addition to the low cost, Kenyan homebrew has significantly higher alcohol.

**India**

India has a long history of large-scale fatalities from methanol-based spirits. In this case, the spirit is chosen based primarily on economy, and not on deceptive labeling. A serving of homemade spirit costs approximately 10 cents per serving. Some vendors add non-potable alcohol to the product to enhance the intoxicating effects. There are several mentions in news articles as Table 4 shows.

The negative effects of significant methanol consumption typically occur much later than the intoxicating effects from ethanol because of the longer time required for methanol to be metabolized into toxic compounds.\textsuperscript{[40]} Significant illicit spirits poisonings, primarily from methanol-based spirits, in India historically include a partial death count shown in Table 5.

As an example, in July of 2022, over 50 people were poisoned with counterfeit spirits in the Indian state of Gujarat, where alcoholic beverages are banned.\textsuperscript{[50]} In Gujarat, the possession or serving of alcohol carries up to a 5-year jail sentence.

In the Report for the Nation prepared by the Authentication Solution Providers Association (ASPA), they state the gray market alcoholic beverage industry was almost 25% of the market in 2020.\textsuperscript{[49]} Illicit categories may be simple counterfeit, smuggled from other jurisdictions, home manufactured, surrogate (alcohols not intended for human consumption such as cleaning products) and tax evasion products (those spirits which were properly manufactured as consumable spirits, but no tax of any type is paid).\textsuperscript{[58]}

**Countries with significant Islamic populations**

In Iran there have been repeated methanol poisonings described in a paper from the Medical Council on Alcohol and the Oxford university press.\textsuperscript{[59]} They show that in addition to the large number of poisonings, due to cultural and religious restrictions and stigma, victims often do not seek medical attention for fear of legal consequences or religious and moral repercussions. This is true however in many areas where there are significant social or religious restrictions on the consumption of alcohol including Sudan.\textsuperscript{[60]}

Table 6 shows a partial list of deaths in both Iran and Sudan. In 2023, there were additional counterfeit alcohol poisonings and fatalities in Alborz, in the north part of the country. As of 18 June, there had been 14 deaths and at least 120 additional poisonings from a single occurrence. Here, the industrial alcohol came from a body spray production facility that had a permit to manufacture cosmetics and health products. Again, it is estimated the death toll is higher as authorities believe many did not seek professional help for the above-mentioned reasons.

**Table 4. News related death announcements in India.**

<table>
<thead>
<tr>
<th>Heading of article</th>
<th>Date of publication</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toxic alcohol laced with methanol kills at least 99 people in India</td>
<td>11 February 2019</td>
<td>[46]</td>
</tr>
<tr>
<td>India: dozens dead after drinking methyl alcohol</td>
<td>27 July 2022</td>
<td>[47]</td>
</tr>
<tr>
<td>Bootleg liquor kills at least 150 in India’s largest mass alcohol poisoning</td>
<td>23 February 2019</td>
<td>[48]</td>
</tr>
</tbody>
</table>

**Table 5. Deaths in India from counterfeit spirit (1976–2022).**\textsuperscript{[46–48,50–57]}

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Deaths</th>
</tr>
</thead>
<tbody>
<tr>
<td>2022</td>
<td>Gujarat</td>
<td>42</td>
</tr>
<tr>
<td>2019</td>
<td>New Delhi</td>
<td>154</td>
</tr>
<tr>
<td>2019</td>
<td>Uttar Pradesh</td>
<td>100</td>
</tr>
<tr>
<td>2015</td>
<td>Mumbai</td>
<td>90</td>
</tr>
<tr>
<td>2013</td>
<td>Uttar Pradesh</td>
<td>40</td>
</tr>
<tr>
<td>2012</td>
<td>Punjab</td>
<td>18</td>
</tr>
<tr>
<td>2012</td>
<td>Orissa</td>
<td>31</td>
</tr>
<tr>
<td>2012</td>
<td>Andhra Pradesh</td>
<td>17</td>
</tr>
<tr>
<td>2011</td>
<td>West Bengal</td>
<td>168</td>
</tr>
<tr>
<td>2011</td>
<td>Pradesh</td>
<td>17</td>
</tr>
<tr>
<td>2011</td>
<td>Sang Rampur</td>
<td>170</td>
</tr>
<tr>
<td>2010</td>
<td>Uttar Pradesh</td>
<td>10</td>
</tr>
<tr>
<td>2010</td>
<td>Kerala</td>
<td>23</td>
</tr>
<tr>
<td>2010</td>
<td>Uttar Pradesh</td>
<td>35</td>
</tr>
<tr>
<td>2009</td>
<td>Orissa Bolangir</td>
<td>30+</td>
</tr>
<tr>
<td>2009</td>
<td>Delhi</td>
<td>30+</td>
</tr>
<tr>
<td>2008</td>
<td>Tamil Nadu</td>
<td>148</td>
</tr>
<tr>
<td>1992</td>
<td>Odisha</td>
<td>200</td>
</tr>
<tr>
<td>1987</td>
<td>Gujarat</td>
<td>200</td>
</tr>
<tr>
<td>1981</td>
<td>Karnataka</td>
<td>308</td>
</tr>
<tr>
<td>1980</td>
<td>Haryana</td>
<td>44</td>
</tr>
<tr>
<td>1976</td>
<td>Gujarat</td>
<td>100</td>
</tr>
<tr>
<td>Total Indian deaths</td>
<td>1975</td>
<td></td>
</tr>
</tbody>
</table>

**Table 6. Deaths in Iran and Sudan from counterfeit spirits poisoning (2004–2018).**

<table>
<thead>
<tr>
<th>Year</th>
<th>Sickened</th>
<th>Died</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iran</td>
<td>2004</td>
<td>62</td>
<td>11</td>
</tr>
<tr>
<td>2013</td>
<td>694</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>2018</td>
<td>768</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>Sudan</td>
<td>2011</td>
<td>137</td>
<td>71</td>
</tr>
</tbody>
</table>
Russia
Russia has a significant history with counterfeit spirit. According to a Business Action to Stop Counterfeiting and Piracy (BASCAP) report in 2012, 45,000 people died in Russia in 2005 and 12,000 died in 2011 from counterfeit spirit.[62]

Turkey
Turkish police described in 2020 the confiscation of 88 tons of counterfeit spirits in bulk and 16,500 bottles of counterfeit spirit ready to sell. In October of 2020 alone, Turkey had 40 deaths and 50 hospitalizations from ingesting counterfeit spirit.[63] As Turkey raises alcohol taxes, they are seeing greater numbers of methanol poisonings.

In December of 2021, at least 26 people died from a single batch of illicit spirit. The issue is the tax increase on alcoholic consumption spirits, to approximately $16.50 USD per liter. During this same time, the Turkish Interior Ministry seized over 30,000 liters of counterfeit spirit and raided 342 locations in a single week.[64]

USA
Because of the nature of recording the illicit manufacturing of spirits, the counterfeit and illicit spirit data in the US primarily are the summation of news reports and social media.[12]

One instance of note was an undercover police investigation in the US state of New Jersey in 2013. They found 29 separate businesses including chain restaurant TG1 Fridays selling an isopropyl alcohol – color – flavor mixture as Scotch whisky.[63] Fortunately, 2-propanol or isopropyl alcohol is much less toxic than methanol, does have intoxicating properties and with low levels of consumption does not generally produce lasting health issues.[65]

Other non-spirits alcohol products
Spirits are not the only problem. It is estimated that over 30,000 counterfeit bottles of wine are sold every hour in China.[66] One example of illicit wine comes from a study of approximately 200K bottles of Domaines Barons de Rothschild exported in 2011. However Chinese export and resale records indicate over 600K bottles of the same wine sold in China.[12]

Acker auction house in the US had auctioned as many as 10,000 bottles of counterfeit wine made by one person. Rudy Kurniawan made wine from low-cost but old red wine and blended and repackaged it.[13] While we will never know the complete economic damage, this one-person defrauded others of millions of dollars.

Methods to detect illicit spirits
As described, the making and selling of illicit spirits have significant impacts both on public health and economies including national, corporate, and personal. Makers of counterfeit spirits often operate with impunity because the actual analytical detection requires expensive equipment, expensive reagents, and highly skilled operators.[67]

There is no standard method of counterfeiting and therefore there is no standard method of detection. For instance, a simple replacement of high-quality spirit with lower quality or less aged spirit of the same category requires different detection practices than would illicit spirit made from industrial chemicals, coloring, and flavoring. As an example, counterfeit Scotch whisky will typically have a different ratio of sugars (sucrose, glucose, and fructose) than would a naturally aged product. Hence methods to view sugar composition that are routinely used include Ultra High-Performance Liquid Chromatography (UHPLC), and Ion Chromatography Pulsed Amperometry Detection (IC PAD).[68]

Each distilled spirit has a large list of other volatile compounds that are specific to both category and specific spirit. There is a vast list of common compounds including acetaldehyde or ethanol (CH₃CHO), propan-1-ol (CH₃CH₂OH), n-butanol (C₄H₉OH), sec-butanol (CH₃CH₂CH₂OH), isobutanol ((CH₃)₂CHCH₂OH), 2-methyl-1-butanol (CH₃CH₂CHCH₂OH) and methanol (CH₃OH) to name only a few that would not be accurately represented by concentration in illicit product. Similarly, the methanol concentration in distilled spirits is low but consistent and not zero, while many counterfeit spirits have significantly larger methanol concentrations.[69]

Investigators have done much to develop and enhance the detection of counterfeit spirits. Analysis can be a direct read of acquired spectra such as from High Pressure Liquid Chromatography (HPLC) or Inductively Coupled Plasma Mass Spectroscopy (ICP-MS). Alternatively, the analysis can be a lower performance system such as UV-Visible spectroscopy, followed by chemometric analysis such as Principal Component Analysis (PCA) or Support Vector Machine (SVM) to name two of the more prevalent techniques. Generally, Gas Chromatography with Flame ionization Detection (GC-FID) remains the primary tool for major volatile congener analysis.

Several methods have been developed to analytically differentiate spirits, usually to investigate a single spirit type. Examples include work to evaluate tequila,[70–75] Scotch whisky,[76] and sugar origin products such as cachaca and rum.[77] There is not significant published material on general purpose or cross-spirit detection of counterfeits. In the case of statistical evaluation of spirit authenticity, a large sample space of similar spirit is required. In addition, the type of investigation must be well defined. Determining the age of a product is a very different analysis than determining trace concentrations of a selected congener.

The illicit spirit investigation methods we examine in this paper have certain common features. Specifically, independent of the type of experiment, one or more of the following are investigated:

1. **Length of aging** – by monitoring organic compounds that are developed in the cask.[78,79]
2. Congener concentration and ratio of higher or oily alcohols.\(^{[80]}\)
3. Adulterant alcohols including methanol and other non-ethanol spirits.\(^{[73]}\)
4. Location of origin by monitoring trace elements or trace mineral ratios.\(^{[72]}\)
5. Process Control of manufacturing.\(^{[81]}\)

Current tests most often involve analytical techniques including but not limited to ICP-MS,\(^{[72,82]}\) Gas Chromatography Mass-Spectrometry (GC-MS),\(^{[83,84,85]}\) Solid Phase Head Space Microextraction (SPME),\(^{[86]}\) ZnO films,\(^{[70]}\) Raman Spectroscopy,\(^{[87]}\) and paper spray sampling.\(^{[88]}\) Further information on these techniques is provided in Table 7.

Current methods to detect illicit spirit may be divided into 4 categories:

**Analytical techniques with no statistical component**

This approach requires the most training for an operator and traditionally requires the most expensive hardware. However, there is no mathematical data analysis; a skilled operator reviews the data and can directly determine the age length, congener inclusion, and authenticity.

MacKenzie and Aylott were able to detect fraudulent Scotch Whisky using GC-MS and HPLC.\(^{[90]}\) They defined counterfeit whisky as spirits that did not have the correct ratio of methanol, n-propanol, isobutanol, 2-methyl butanol and 3-methyl butanol. They searched for other well-known Scotch congeners to verify it was the age stated. In the paper they use basic specific gravity measurements for the total alcohol, and gas chromatography to search for specific amounts of the largest congener contribution. Using HPLC they look for low levels of Scotch whisky components that come from the aging process.

In addition, they present 18 separate case studies wherein they analyze the liquid contents and review spectra to decide if it is an adulterated sample or not. For example, in one case study, they determine the levels of isobutanol, and n-propanol are lower than should be found in properly aged Scotch and therefore it was a counterfeit specimen. In the end however they use multiple extremely expensive systems, that require expensive reagents and traditionally require a PhD level operator. The advantage is direct interpretation of data, that does not require additional analysis.

Boscolo et al. also use gas chromatography to observe volatile chemical compounds in Brazilian spirits.\(^{[84]}\) In their study they use high-resolution gas chromatography with a flame ionization detector. This system, ranging in price from about $20K USD to over $60K USD, requires highly skilled operators. These systems generally require very pure analytical grade chemicals as standards. Ultimately, they are looking by direct analysis for ratios of volatile compounds that are not recreated in counterfeit spirits. Therefore, for analysis it is required to have the expertise to understand and interpret the chromatograms acquired. They can determine levels of naturally occurring methanol in samples, however this technology would be impractical to use for daily investigation of non-genuine spirits due to its complexity and expense. Table 8 lists Group 1 methods and authors. It should be noted these methods give excellent results but are the most expensive devices and require the highest level of training for both experimental operation and data analysis.

**Analytical techniques with some statistical data reduction**

Oliveira et al.\(^{[89]}\) discussed the use of chemometrics and statistics to take data and extract results statistically. Specifically with the appropriate data treatment, a spectrum that is not able to be interpreted directly can be understood post statistical analysis.

They have used this to high accuracy to detect the addition of methanol or industrial ethanol. Their study was a meta-study, looking at previously acquired data, that was
Table 7. Technologies used in the detection of counterfeit spirit.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Description</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>Gas chromatography-mass spectrometry (GC-MS)</td>
<td>This technique will vaporise a sample and flow the vapor along with an inert carrier gas through a thin or constricted tube called a column. The purpose of the column is that different components of the sample flow at different rates. The column is fabricated in a fashion that causes different interactions between the vapor and the column, depending on specific characteristics. The column is typically heated and as the compounds and inert gas exits the tube, there is a detection apparatus. If this detector is a mass spectrometer, this technique is called GC-MS. Other detectors can include thermal conductivity detectors and flame ionization detectors. Each detector has its specific applications. For instance, the flame-based detectors are most frequently used when the sample under test is hydrocarbon based. Both GC and GC-MS are excellent technologies that can provide information that can be admissible in most courts. If available and practical it is always first choice. However, the systems can be expensive to purchase, expensive to maintain consumables and often will require a highly skilled and trained operator. In addition, they are not portable or handheld.</td>
<td>[89]</td>
</tr>
<tr>
<td>High-performance liquid chromatography (HPLC)</td>
<td>This technique uses a column packed with a separation medium. The sample in liquid phase is injected through the column and different specific compounds will separate through differential migration. The sample continues to flow as the compounds segregate in the column. As the sample liquid that is now segregated by compounds emerges it is passed through a detector that will generate time-based spectra. The detector can be chosen to best analyze the sample under test and can include UV-visible spectrometry, a photodiode, or a mass spectrometer.</td>
<td>[75,90]</td>
</tr>
<tr>
<td>Schlieren optical technique</td>
<td>This technique tracks changes in refractive index in an optically uniform and transparent medium. Cooled light passes through the medium and produces a shadow image on a screen or detector. If no effect causes media perturbation, there is no shadow image. When there is an effect that causes a distortion in the otherwise uniform medium, an effect is manifest on the detector or screen. This effect is useful when all components under study are transparent. In this case, the transparent media is deionized water that is continuously flowing in a carrier stream. Precise volumes of the spirit sample test under test are injected into the carrier stream. The physical system limits mixing, and the detector looks at refractive index gradients. The collected data is analyzed using the supervised chemometric method SIMCA (Soft Independent Modelling by Class Analogly).</td>
<td>[91]</td>
</tr>
<tr>
<td>1H NMR</td>
<td>This is a method to observe the spin-flip of the hydrogen nucleus with the application of sweeping radio frequency (RF) energy typically under 100 MHz. This spin-flip coupling occurs at a ‘resonance’ which is when the spin flips from one orientation to another. The antenna or resonator coil produces an RF pulse which causes the spin flip at resonance, then subsequently measures the energy that is emitted when the protons return to their initial alignment. While all isolated protons would behave similarly, close by electrons provide shielding effects, reducing the RF-proton coupling. NMR data is very good at determining structural information of intact molecules from very small samples with little sample preparation.</td>
<td>[79]</td>
</tr>
<tr>
<td>Inductively coupled plasma atomic emission spectroscopy (ICP-AES)</td>
<td>This method will detect elements in a sample. The device is two systems – the plasma generating system and the spectroscopy system. The plasma generating system will use RF coils to produce a plasma in typically argon gas. The sample under test is introduced in the small concentration in the plasma. The charged plasma ions of the argon will collide and interact with the sample producing sample charged ions. The second system is an optical spectrometer that can determine the optical emission of the excited elements. The brightness of each characteristic emission is proportional to concentration. The detected spectra can be compared with previously measured reference spectra to determine concentration. Compounds are not detected because the conditions in the plasma will decompose compounds to their constituent elements. Compounds can be ionized by ionizing methods can be used as well as a variety of reagent gases.</td>
<td>[72]</td>
</tr>
<tr>
<td>Headspace solid phase microextraction (SPME)</td>
<td>A method of capturing either liquid or volatile compounds on a prepared fiber and subsequent detection using the previously described GC-MS. Here a fiber is coated with a material that will absorb specific compounds. The fiber is typically housed and protected in the bore of a hypodermic or sample needle. During sample collection the prepared fiber is introduced to the sample, adsorbing material. At this point the fiber is removed from the sample and subsequently introduced to a GC-MS system where fiber heating causes de-absorption of compounds and allows the compounds to be introduced to the GC-MS for analysis. The fibers do not cause harm to the sample under test, can be reusable, and do not generally require solvents. This is a low-volume selective sampling technique for GC-MS.</td>
<td>[78]</td>
</tr>
<tr>
<td>Chemical ionization mass spectroscopy (CIMS)</td>
<td>This technique uses an approximately 99% chemical ionization reagent and approximately 1% compound under test and a variety of ionization means including photon impact, electron impact or other means to produce ionization of a sample. After ionization the compound fragments are introduced to a conventional mass spectrometer. Significant values of CIMS are that a variety of ionization methods can be used as well as a variety of reagent gases.</td>
<td>[85]</td>
</tr>
<tr>
<td>Raman spectroscopy</td>
<td>An optical technique to provide characteristic spectra of chemical compounds. Because of the ability to characterize samples quickly and accurately, handheld devices can be used to detect many types of contraband including counterfeit spirits. While these devices can be quite compact, allowing investigators to quickly and oftentimes through the bottle, determine if a sample is genuine or has been adulterated.</td>
<td>[30,87]</td>
</tr>
<tr>
<td>ZnO</td>
<td>Initially small patches of evaporatively deposited Zn are fabricated on a ceramic substrate that is subsequently oxidized. Different durations of oxidation and different temperatures during oxidation change the characteristics of each patch. Each small patch subsequently has conductive electrodes deposited at each end for connection to an electrical resistance measuring system. As ethanol is absorbed on the deposited patches, the resistance of the ZnO changes and corresponds to the concentration of adsorbed materials. Upon drying the resistance returns to original baseline.</td>
<td>[70]</td>
</tr>
</tbody>
</table>

(Continued)
Table 7. Continued.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper spray mass spectrometry</td>
<td>A straightforward method of collecting a small liquid sample on an absorbent porous paper that is connected to a high voltage power supply. This is an extension of electrospay ionization which is perhaps more commonly known. A solvent is added to the paper-based sample and an applied voltage creates ions in free space of the sample material. As the droplets are in free space and are moving under the applied field, the microdroplets dry and in turn become gas phase materials as they enter the mass spectrometer for conventional analysis.</td>
<td>[88]</td>
</tr>
<tr>
<td>Alcoholic spirits methanol test strips</td>
<td>One method not reviewed: These inexpensive products test for very low concentrations of methanol, and if this is a concern, are recommended, but do not test for or give any indication of any other adulterant. Current EU limits for naturally produced methanol in spirit drinks is 0.4% (v/v) methanol at 40% (v/v) ethanol. All techniques reviewed can adequately detect this level.</td>
<td>[92]</td>
</tr>
<tr>
<td>Chemometrics</td>
<td>While there are several techniques that either collectively or individually known as chemometrics, many of them attempt to classify data, oftentimes in a new or abstract coordinate frame such as Principal Component Analysis (PCA) or Partial Least Squares – Discriminate Analysis (PLS-DA). Papers will frequently mention pattern recognition. This is a consequence of chemometric methods – taking a large data set and finding in the data previously unseen clustering that indicates some commonality.</td>
<td>[30,70,72–75,87]</td>
</tr>
</tbody>
</table>

Table 8. Grouped technologies used in detection of counterfeit spirit including success/detection rate.

<table>
<thead>
<tr>
<th>Group</th>
<th>Technology</th>
<th>Success/ Detection rate</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Analytical techniques with no statistical component</td>
<td>GC-MS, HPLC</td>
<td>Complete detection</td>
<td>[90]</td>
</tr>
<tr>
<td>2. Analytical techniques with some statistical data reduction</td>
<td>Pattern recognition</td>
<td>&gt;90%</td>
<td>[89]</td>
</tr>
<tr>
<td></td>
<td>Schlieren effect</td>
<td>100%, 93%</td>
<td>[91]</td>
</tr>
<tr>
<td></td>
<td>Chemical ionization mass spectroscopy</td>
<td>92%</td>
<td>[85]</td>
</tr>
<tr>
<td></td>
<td>Headspace solid phase microextraction</td>
<td>94%</td>
<td>[78]</td>
</tr>
<tr>
<td>3. Optical detection with no statistical analysis</td>
<td>'H NMR</td>
<td>95%</td>
<td>[79]</td>
</tr>
<tr>
<td></td>
<td>ICP AES</td>
<td>95–100%</td>
<td>[72]</td>
</tr>
<tr>
<td>4. Optical detection with statistical evaluation</td>
<td>UV-visible spectroscopy + Chemometrics</td>
<td>&gt;90%</td>
<td>[73]</td>
</tr>
<tr>
<td></td>
<td>Handheld Raman + Chemometrics</td>
<td>'Promising'</td>
<td>[87]</td>
</tr>
<tr>
<td></td>
<td>Handheld Raman + Chemometrics</td>
<td>'Promising'</td>
<td>[30]</td>
</tr>
<tr>
<td></td>
<td>Handheld UV-visible spectroscopy + Chemometrics</td>
<td>Similar to HPLC</td>
<td>[75]</td>
</tr>
<tr>
<td></td>
<td>Handheld UV-visible spectroscopy and Chemometrics</td>
<td>86.3%</td>
<td>[70]</td>
</tr>
<tr>
<td></td>
<td>Handheld ICP AES + Chemometrics</td>
<td>&gt;94%, 98%</td>
<td>[72]</td>
</tr>
<tr>
<td></td>
<td>Handheld UV-visible spectroscopy and chemometrics</td>
<td>'Effective'</td>
<td>[74]</td>
</tr>
</tbody>
</table>

obtained from a variety of means. The collected data was analyzed using the chemometric tools PDA, LDS-DA and SIMCA. They did show that common grouping did occur in the chemometric analysis.

Da Costa et al. use the Schlieren effect as the probe.

They state that a given spirit has a specific optical index of refraction that is the result of the ethanol but also the other volatile compounds present. For this analysis, they searched for changes in index of refraction between the claimed spirit, the known good, and the spirit under test. The investigators state that it is unlikely that the index will be identical between a counterfeit sample and a sample that is legitimate. They concluded stating that 93% of the test samples were correctly identified as fake and the overall SIMCA statistics process had a 95% confidence level. This technology can be significant for other investigators, and due to the low-cost of the instrument, investigators could easily duplicate the experiments to determine if the same results are forthcoming.

Smith uses one of the most complex apparatuses in this review – a Desorption Atmospheric Pressure Chemical Ionization Mass Spectrometer or DAPCI-MS. The system is complex and expensive, and the reagents and sample preparation are involved, very nuanced, and susceptible to contamination and operator error. The operator must have an abundance of knowledge of the samples under test as well as the reagents and the water. Additionally, the operator must understand the proton affinity of the solvent and sample and adjust the operating parameters accordingly. After the data is acquired, the authors use PCA to reduce the data and then PLS-DA for classification. However, they achieved only a successful classification rate of 92%. This method is expensive, time consuming, non-intuitive and only performs marginally better than the poorest performing experiments reviewed herein.

Belmonte-Sanchez demonstrates a fingerprint (specific compounds in specific ratios) analysis using Solid Phase microextraction with standard chemometric techniques including PCA and LDA. This elaborate and time-consuming technique uses a 100-micron fiber made of polydimethylsiloxane (PDMS) as the microextraction device and uses GC-MS for detection. After GC-MS, they used HCA, PCA and LDA to determine up to 40 specific ions that in turn pointed to 13 specified compounds. Their best classification percentage was 94%. In conclusion this is an overly complex and expensive method to determine the fingerprint of rum samples. This same work can be done more easily, as will be shown, using UV-Visible spectrometry with PCA.

The same research group later used 'H NMR to again classify rum. They describe a complex data taking schema starting with 'H NMR, feeding into gas and liquid chromatography and in turn feeding into mass spectrometry. Ultimately after the data acquisition, they use PCA to reduce the size of the data set. They arrive at approximately 95%
classification accuracy. The authors 'classify' rum but do not define what is meant by the word 'classification'. Ultimately, they can determine what raw materials are used (sugarcane, molasses), what the distillation method is (pot or continuous), if it can be defined as 'old' or 'young', and if it was stored in French oak or American oak barrels. This paper presents interesting results, but with significant expense, operator requirements and reagent needs.

Ceballos-Magana and team in 2012 examine and determine authenticity of tequila by means of mineral content using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) together with PCA. They state that each location where the spirit is made has different naturally occurring minerals and therefore mineral ratios in the manufacturing and dilution water will be evidence of the point of manufacturing. The experimental sample preparation is time consuming and requires caustic and toxic compounds including nitric acid and vanadium pentoxide as part of the experimental requirement. The latter compound costs over $220 USD for 250 grams of material and is a suspected mutagen, carcinogen, and is suspected of causing reproductive harm. In addition to a complex and expensive system, the manufacturing company is out of business so exact experimental duplication will be difficult.

Their claim is that every distillery uses a different water source and therefore the trace minerals will be different and will provide evidence of location of manufacture. They state that a fraudulent product will most likely not use the same water as was used at the distillery. ICP-MS data can be very feature rich, and therefore yields itself well to PCA to reduce the data size significantly. After they reduced the data set, they used LDA and finally SVM. They were able to determine authentic from fake with between 95 and 100% successful differentiation. So, while the process works in a successful fashion, the complexity and expense are challenging for more mainstream adoption.

Distillation and aging of spirits makes a very large number of volatile compounds such as hexanol, decanol, and methyl decanoate. Frainitza et al. use Solvent Assisted Flavor Extraction (SAFE) to determine specific volatiles and their concentrations. Their notion is every spirit type will have a specific ratio and concentration profile of volatile compounds. They start with isotopically labeled standards. These chemical compounds have a carbon (13C) or a hydrogen replaced by 2H (deuterium). The work also requires comparison with legitimate spirits to arrive at the correct ratios. Once data has been collected the authors use PCA to reduce the vast complexity of data to 3 dimensional plots. The authors were able to classify unknown spirits at a rate of 88%.

Gonzalez-Arjona et al. used what we now see as standard equipment, a Fisons GC 8000 gas chromatograph and a mass spectrometer. This work is significant because they applied a very large range of separate statistical treatments to determine which one(s) had the best efficacy. Specifically, they want to find a single set of discrimination rules to distinguish between whiskies including bourbon, Irish, and single malt Scotch. The authors identified many volatile alcohols or congeners in the spirits. Some were in all the samples tested and others were in a smaller subset.

After collection of the GC-MS data they applied, on the same data sets, statistical treatments including k-Nearest Neighbor (KNN), Linear Discriminant Analysis (LDA), Soft Independent Modeling of Class Analogy (SIMCA), Multi-Layer Perceptron (MLP), and Probabilistic Neural Network (PNN). Generally, these were packaged programs run in MATLAB except for KNN which the authors wrote in QuickBasic. Most of the statistical treatments were able to discriminate the differences completely except for SIMCA, which was the least successful of the routines investigated. The significant value of this paper is the wide-ranging statistical treatments with a common data set. It is also interesting that for instance PNN is complex to administer and did not do any better than some of the simpler to implement choices such as PCA. Table 8 recaps the various technologies used in group 2.

Optical detection with no statistical analysis

Frasier and Frances investigated spirits using two completely different but low-cost and useful methods - low power ultrasound and UV-Visible spectroscopy. Specifically, they were investigating if they could characterize the aging times of spirits using these two means. Some spirits can be sold as legitimate while not having been aged to the claimed term. Others are so called rapid aging products and the authors attempt to determine if there is different chemical composition that can be identified. The ultrasound investigation takes advantages that the different trace levels of congener alcohol produce in aggregate different densities and therefore the speed of sound through the spirit will be measurably different than a spirit that was not aged as long.

Additionally, the same team showed that similar spirits, aged in a similar cask had very significant changes to their UV-Visible spectra because of aging. Longer aging did not necessarily mean a higher amplitude spectrum. Using a discrimination technique to find counterfeit spirits, the authors could probe through the bottle, matching an observed spectra to a known spectrum. This can be useful, and very inexpensive to implement and does not require highly trained technicians to operate. Both methods, UV-Visible spectroscopy, and low-power ultrasound, in this study, produced encouraging results indicating that there is much promise for these complimentary techniques in a commercial environment, however the authors did not compare their results against more commercially established techniques. Generally, where there are optical spectroscopy means used, there are also statistical or chemometric methods used in data analysis. Table 8 recaps the technology used in Group 3.

Optical detection with statistical evaluation

Generally, the lowest cost, lowest complexity analytical system is a UV-Visible spectrometer. This however is not well suited for direct reading analysis. Statistical tools including PCA, SVM and PLS-DA can provide the following benefits:
1. Massively reduced data.\(^{[79]}\)
2. Statistically relevant discrimination from very low frequency data.\(^{[72]}\)
3. Lowest cost of data acquisition instrumentation.\(^{[87]}\)
4. Low to no reagent chemicals required.\(^{[90]}\)
5. Lowest operator skill required.\(^{[75]}\)

There are a significant number of papers addressing counterfeit tequila using UV-Vis spectroscopy with statistical means.\(^{[70,72,74]}\) Barbosa-Garcia et al. were able to differentiate between 60 different tequilas using this method.\(^{[71]}\) Specifically, their goal was to determine if the spirit under examination was indeed from 100% blue agave origins or if it comes from a mixed plant source – which is a lower cost product but can be often sold as premium.

They were able to show that using PCA with a good training set (to develop the needed statistical metrics) they can achieve an 85% probability of finding a sample of a specific brand. In the same study, using PLS-DA, and a small training set, they can correctly identify 75% of the high-quality product and 80% of the lower quality product. While this is a lower result than has been seen with GC-MS, ICP-MS and others, the analytical instrument can cost 1/100 of the more sophisticated device and the operation is much simpler. Also given a greater training sample, the statistical values become better.

Cantarelli et al.\(^{[95]}\) looked at premium Scotch whiskies using UV-Vis spectrometry with a low-cost spectrophotometer made by Ocean Optics. In their method, the samples are both diluted with water, and buffered to pH 12. The resulting spectra was essentially featureless. However, PCA and other statistical methods can reliably extract the counterfeit from the genuine product.

In this study, they were looking for adulterants such as methanol and other industrial alcohols, dyes and added flavors; all compounds that should not be found in legitimate Scotch whisky. After the spectra were taken and recorded in tables, the data dimensionality was reduced significantly using PCA. After PCA, basic pattern recognition was performed using LDA and PLS-DA chemometric techniques.

After this statistical analysis, 99.15% were correctly categorized according to trademark and 100% were correctly categorized by age ranking. This performance was at least as good if not better than many of the vastly more expensive schema such as GC-MS.

One of the best examples of an extendible and generalizable technique is demonstrated by Contreras et al.\(^{[73]}\) They use simple to operate and low-cost UV-Visible spectroscopy and then a competent application of chemometrics including LDA, SVM and PCA to determine if a given tequila is fake or genuine. In their study they are not looking at a specific chemical adulterant or missing component. Rather they analyze spectra from both genuine and fake product and the statistical analysis, when competently applied, can predict the real from the not with an almost perfect success rate.

They acquired multiple spectra from a large body of potential samples – both real and counterfeit. They simultaneously ran a FT-IR study to chemically determine experimentally the real and counterfeit samples. After data is acquired, they use PCA to reduce the dimensionality of the huge UV-Vis data set. Specifically, they had 80 data sets and examined the spectra from 250 to 500 nm. This is 20,000 individual data components. After PCA, they determined that only two components or 160 pieces of data accounted for 99.99% of the total spectral variation and even better, just one component accounted for 97% of all the spectral variation.

Ultimately, they were able to determine counterfeit with a high degree of success. Because this is a purely statistical analysis, they were able to determine over 90% of the counterfeit with over a 90% confidence factor. Considering the spectrometer could be as inexpensive as $90 USD and the software can be opensource, this is absolutely a channel that needs more investigation to apply both to rum and to spirits generally.

Ellis et al.\(^{[30,87]}\) were able to use exclusively optical means to investigate counterfeit spirits through the bottle, with no opening required. Specifically in 2017 the Ellis group were looking to detect ultra-low levels of methanol using the Resolve handheld Raman Spectrometer. These devices are usually employed to detect contraband at airports and by the police.

It is worth noting that the named handheld spectrometer costs approximately $65,000 USD. This work was a direct observation using no statistics, mostly as a function of the quality and sophistication of the detector they were using. That is, the device, made now by Agilent, optically probes a sample using an infra-red laser and has an on-board database of drugs, explosives, and adulterants. The team acquired the device and used it. None the less, it was able to detect very low levels of methanol through colored and clear glass.

In 2019, the same group were looking for a methanol adulterant. They used a portable Raman spectrometer in the infrared at 1064 nm. They were able to detect, in the bottle, methanol concentrations as low as 0.23% v/v. They looked at a variety of samples including whisky, rum, gin, and vodka and were able to detect low concentrations of methanol through clear, blue, green, and brown bottles for all spirit classes. In addition, this spectrometer is handheld, with an 11-h battery lifetime. This promising through the bottle approach using Raman then using chemometrics is worth pursuing as a mainstream technology. Table 8 recaps the various technologies used in Group 4.

**Worldwide efforts to combat illicit spirit production**

There is no universal fix for the illicit spirits problem. Some produce for commercial economic gain, while others produce illicit spirit because their community cannot easily afford higher priced authentic spirits and willingly purchase non-authentic products.\(^{[14]}\) Distribution channels and types of spirits produced are both region and economy dependent, and each provides unique challenges. Low quality inexpensive illicit spirit represents a massive public health problem due to the high inclusion of methanol and other non-potable
compounds, and high-end spirit counterfeiting represents a significant marketing problem for commercial manufacturers. In addition, marketing, and sales of fake spirit through online means represents another significant distribution channel that is difficult to regulate. Even in less developed or underdeveloped areas, the online sales of fake liquor have significant distribution networks in place.

There are steps that may be taken to reduce adulteration of packaged products. Closures and labels that are tamper-proof help with issues of repurposing, and labels and boxes that have difficult to print images do help to detect non-legitimate product. Such methods do help to keep bottles and closures that leave facilities from being reused, but have little control when bottles, labels and closures are made to look like actual original product. There is growing use of digital product passports and tracking of packaging through use of near-field communication (NFC) tags, quick response (QR) codes, or covert security features such as Cryptoglyph™ and Fingerprint™. Blockchain has also been successfully applied to tracking products and applications are available to identify products that are scanned ‘out of zone’ from defined supply chains or markets.

Although packaging can be labelled and tracked, brand owners do not typically detect or authenticate spirit. This is usually a task for independent testing labs that have been contracted by law enforcement or private individuals. Generally, enforcement of counterfeiting is handled by law enforcement officials, and not the distilleries. In addition, there are trade associations such as the Scotch Whisky Association, that provide policing and investigation.

When suspected counterfeit spirit is analyzed, methods described in this paper will be used with the most common being GC-MS, HPLC, and NMR testing. Methods to determine alcoholic strength and to measure congener concentrations and types are important for many categories of spirits. The determination of specific congeners and concentrations can yield accurate fingerprinting of specific spirits. Manufacturers have made available portable spectrometers to investigate potential counterfeit spirit using Raman spectroscopy, which will determine chemical composition through the glass of the bottle. However, routine analysis of spirits is out with the typical budget of individual distilleries, and the main mechanisms for prevention of counterfeit spirit production lie with regulation and law enforcement.

Law enforcement of spirits counterfeiting is variable on a case by case and country by country basis. As described below INTERPOL through their operation OPSON program have over the years removed thousands of bottles of counterfeit spirit and millions of dollars of potential illegal revenue.

The Alliance Against Counterfeit Spirits (AACS) stated that since Jan 1 of 2012, their activities have resulted in over 4 M bottles of counterfeit spirit being seized, the confiscation of over 3.6 M fake closures (caps and corks), as well as over 17 M fake labels. In addition, they state that simply from their actions there have been over 11.7K anti-counterfeit enforcement actions. Also, they have trained almost 17K law enforcement officials since 2012 to have specialized knowledge in detection, tracking and apprehension of counterfeit spirits.

INTERPOL together with Europol conducted a multicounty operation, called Operation Opson, which was started in 2011 with only 10 countries. By 2015 and 2016, Operation Opson V saw 57 countries participating and by 2018, there were 67 countries involved, as well as 22 private companies. Opson V ran from November of 2015 through February of 2016. While they were involved with many types of counterfeiting, they did seize approximately 1.5 million liters of liquid counterfeit products including spirit. The operation extended to even Zambia where officials found 1300 bottles of counterfeit spirit in genuine packaging. The unused original packaging was taken from a warehouse. Operation Opson XI confiscated 15 million liters of counterfeit and illicit alcohol and caused over 175 criminal cases to be opened. In Opson IX, $5.8 M USD worth of counterfeit alcohol was seized, and 408 criminal cases opened.

From the same OPSON V study, over 10% of sampled and tested spirits from Bulgaria, Spain, Greece, and Cyprus were counterfeit, and over 11% of Lithuania’s. Also, the study showed that in both Poland and the Netherlands approximately 2.5% of spirits are typically counterfeit. This illustrates that in countries where there is a stronger rule of law, counterfeiting can be kept lower. However, incomplete national law enforcement records can give the same implication as lower production. In Opson VII, alcohol was the most seized counterfeit product from a monetary standpoint.

As a result of the deaths in the Czech Republic during 2012–15, one of the consequences was banning the sale of all spirits greater than 60 proof. Subsequently, the restriction was increased to include 40 proof spirit and greater. Further effects included the outright ban of methanol for products including window cleaning compound to remove those compounds from availability.

Also in the Czech Republic, Diviak et al. used trackable poisonous spirits to develop a testable model of the organized crime distribution network. They studied 32 convicted criminals, used legal records, and applied a social network analysis (SNA) to determine the hierarchy of the criminal enterprise. They developed sociograms of in-place relationships, and hence could determine the degree of organization of the criminal structure.

Due in large part to the Czech government, significant reduction of spirits of all types and heightened attention to liquor counterfeiting, there is very little illicit liquor detected today, with the largest channel for untaxed alcohol now wine.

The Italian Guardia Di Finanza found and removed more than 9000 finished and ready to sell bottles of Moet & Chandon champagne, worth €350,000 and an additional 40,000 labels, which if sold would have been worth €1.8 million for a single operation total of €2.15 million. Between December 2019 and June 2020, a joint operation directed by the European Anti-Fraud Office (OLAF) confiscated over 1 million liters of counterfeit alcohol of all varieties including wine. This was part of the previously described OPSON IX operation.
In 2020, in Mexico, law enforcement confiscated and destroyed 200,000 liters of illicit tequila. They stated this is the equivalent of almost 7 M separate drinks. This was the 23rd legally provided liquor destruction, and only the 4th largest. They stated that over 3.5 M liters of fake tequila had been destroyed since 2002. For comparison, Mexico made approximately 350 M liters in 2019. [106]

In 2018, the Israel Ministry of Health confiscated 1760 bottles of counterfeit spirits. Upon testing, these samples were found to contain methanol as much as 500 times higher than the legal maximum of between 7 and 12 mg/L depending on the spirit and the country. These bottles were intended to look authentic and were labeled “LOUIS XV, Brandy Flyajka.” [107]

A disadvantaged neighborhood in Tel Aviv was investigated for the inclusion of adulterants in samples of spirits. The study found dangerous substances in over 50% of the spirit samples tested. Investigation with local hospitals did not however indicate many methanol poisonings. This is noteworthy because it further illustrates the divergence between the measured quantities of adulterated spirit and the various indirect methods used to arrive at similar results. [91] In this case, social or religious practices may have affected the narrative.

In 2021, Realnoe Vremya [92] discussed the Russian government practice of both raising state prices on spirits generally, as well as increasing tax on spirits by 4% because of the increasing costs of raw materials. However, during that year (2021), the price of wheat increased by 50% and the price of wood pallets increased by 200%. Realnoe Vremya speculates that the raw materials price increase caused illicit spirits sales to increase and legitimate spirit sales to decrease because counterfeit products do not have the same limitations including starting raw materials costs as do conventional product. If the alcohol is industrial ethanol or methanol, the pricing pressures will not be equivalent to that of conventional and legitimate products. They state that in the first 9 months of 2021, Russian officials closed over 700 counterfeit manufacturing facilities. The increase in excise tax in Russia was described as a method to combat alcohol abuse. However, because of lax penalties for counterfeit spirit manufacturing, the increased state price can open the door for cheaper product illegally brought into Russia from places including Kazakhstan (with 50% less VAT) or Belarus (with 20% less VAT). [92]

Rehm et al. (2022) investigated if changing or increasing taxation on alcohol determines first order changes in illicit alcohol consumption. The issues are ‘does increased official tax on alcohol cause the population to move to illicit alcohol because of significantly reduced cost’, and ‘what is the best or most successful policy to be implemented’. They determined that while planning and taxation should implement increased fees on alcohol with caution, there is no direct evidence that there is significant untaxed alcohol consumption encountered if mitigation and controls are implemented in parallel. [94] Kenyan alcoholic law is a study in the unintended consequences of governmental policy. They experimented with a lower alcohol excise tax to allow legitimate products to compete with illicit products. However, this caused an increase in alcohol consumption and increased alcohol morbidity. They tried taxing or an outright ban on toxic compounds however, there was not enough manpower or funding to enforce these laws. Finally, they experimented with a government monopoly on the manufacture of alcoholic spirits. However, this effectively created an unwanted endorsement by the government of a product that has significant health and social implications. [42]

The Russian invasion of the Ukraine and the associated worldwide sanctions have reduced the number of imported spirits to Russia. Both international sanctions against business in Russia, as well as individual companies boycotting Russia in general has reduced legitimate spirits there. As of 2023, Diageo states they are “…not either directly or indirectly importing or selling any products in Russia”. This is in response to a raid in Moscow of a company making and bottling counterfeit Jonnie Walker Black Label. However, in response to this, Russia has increased its ‘gray-market’ importation channels. The Beluga Group plans in 2023 to import over 300,000 bottles of Jonnie Walker even though it is not sanctioned by Diageo. This is however endorsed by the Kremlin. [108] In 2022, Russia provided legislation to promote premium spirits brands, without the distributor, manufacturer, or trademark holders’ permission. This is primarily using countries that remain aligned with Russia including China, Kazakhstan, and Turkey.

While it is clear there is a large quantity of illicit spirits manufactured in the US, there is not a large amount of law enforcement. Moonshine is so prevalent there are widely watched television programs solely based on the manufacture of illicit spirit. One significant and widely reported case was that of Marvin “Popcorn” Sutton who was arrested in 2009 after offering for sale 1000 gallons of illicit moonshine whisky to a US federal agent. For this crime he only received a sentence of 18 months. [109] This criminal was so overt that he had printed business cards, formerly stating ‘…you can't sell it if no one knows you got it…” [34]

Regardless of what is publicly stated regarding the US position on counterfeit spirit, the budget and number of agents assigned to this enforcement indicates this is a low priority issue.

Conclusions
Illicit spirits are clearly shown to have significant and asymmetrical health effects worldwide. In areas where financial constraints compel consumers to purchase counterfeit products, sickness and mortality can occur in disproportionate numbers. Illicit spirits reduce employment, corporate revenue, and local and national taxes. Also, enforcement is not uniformly applied across a given country and certainly not from country to country. In many instances there is social, religious, or governmental pressure to underreport the total amount of counterfeit spirit detected.

Certainly not all illicit spirits are acts of deception against the consumer. The issues of lower priced spirits with consumers willing to purchase illicit spirits, or the high-end spirits where the act is most certainly one of deception segregate with no obvious overlap. Most health
issues occur from willing participants purchasing highly discounted spirits while most of the tax theft, lost revenue and brand erosion come from consumer deception.

There are opportunities for fighting counterfeit products of all types but no one process will solve this problem. Regulation and taxation have varying degrees of success in terms of reducing incidences of counterfeit spirits entering the market. New packaging and tracking systems, and novel labels and closures, are all proactive methods that may be used to reduce adulteration of packaged spirit. In this review, a range of methods have been described for spirit analysis and each has shown merit in identifying the counterfeit or adulterant, however common limitations include significant expense and training level required to operate. Criminal prosecution will usually require data obtained by one of a few analytical techniques described such as GC-MS and HPLC, but statistical and indirect techniques have significant value in the screening of large numbers of market samples particularly when investigating the scale and distribution of an illicit alcohol health incident. Of all methods described in this review, UV-Visible spectroscopy with PCA is the easiest method to implement, the cheapest to run, and generally as predictive as the other methods.

Looking forward, a systematic effort is needed to combat the problem of counterfeit spirit production. This includes tougher legislation and greater deterrents, such as increased fines, but also much wider detection. The development of tougher legislation and greater deterrents, such as increased legislation, without opening a bottle and even through colored glass, is key, as are improvements in sensitivity of ‘gold standard’ methods, in statistical analysis, and the availability of a standardized database of information for use by industry and agencies worldwide.

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