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Review

The future of wine packaging—A perspective

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Abstract: This paper aims to investigate and compare different wine packaging options, with a focus on improving the environmental sustainability of the wine industry. The traditional glass wine bottle, while iconic, contributes significantly to the carbon footprint of wine production, accounting for approximately 30% of the environmental impact. Winemakers are actively exploring alternative packaging solutions, such as bag-in-box, Tetra Pak, polyethylene terephthalate (PET) bottles and cans, to reduce the industry's overall environmental footprint. The research not only examines the impact of different packaging options on wine quality, but also addresses broader sustainability considerations, including waste management, recycling challenges, degradation concerns and ecotoxicological issues. The exploration of consumer expectations and trends adds a crucial dimension, recognising that sustainable packaging is not only in line with environmental objectives, but also with evolving consumer preferences and industry trends. This comprehensive research aims to inform the wine industry of the implications and potential benefits of adopting greener packaging practices.

Keywords: wine packaging; plastic bottles; glass bottles; bag-in-box; cans; sustainability; recycling; waste management

1. Introduction

The value chain of wine packaging has undergone many changes and innovations throughout history. The first vineyards were discovered in Armenia [1], dated to the early 4100s BC, and with this discovery came the first known material used to store wine, earthenware vessels [2]. In addition to being the oldest storage containers for wine, earthenware vessels were used at every stage of wine production, from crushing the grapes to aging the wine.

For many years, it was thought that amphorae were used to transport the vast majority of wine over long distances in the Roman Empire. Recent discoveries of shipwrecks throughout the Mediterranean have shown that wine was often transported in a larger container called a dolium [3]. By the third century AD, the Romans had adopted wine from the Gauls in France [4]. They used wooden barrels instead of ceramic vessels because of their earlier experience with beer stored in wooden barrels. The Celts are credited with inventing the wooden barrel, but the Gauls adopted it from the Romans. Although the Romans knew that other, earlier civilisations had used palm wood barrels to transport wine, amphorae, and dolia were the preferred means of transporting wine until they met the Gauls.

Barrels were made in various sizes, including the *tun* (equivalent to 954 litres), which was the measure of wine used in most medieval import and export documents [2]. However, the wood did not provide an airtight seal, and the wine spoilt quickly when stored in wooden barrels. Not understanding the causes of wine spoilage, winemakers didn't bung or fill their barrels correctly, and people began to consume younger and younger wines. This practice led to the disappearance of vintage wines in medieval times. After centuries of the dominance of wooden barrels and the urge to drink wine quickly before it turned to vinegar, winemakers began to look for an alternative solution.

Although wine continued to be stored and transported in barrels until the 20th century, cork and glass bottles were introduced in the 17th century. Advances in glassmaking allowed for the manufacture of thicker, harder to break glass. Eventually, the point was reached where wine could be safely stored and transported in a glass bottle. Early wine bottles had wide bottoms and short necks. Over time, the neck lengthened and the bottom slimmed, and by the 1820s, shapes already resembled the wine bottles we know today.

Glass is the most widely used container for wine [5,6]. However, the production of glass bottles requires huge amounts of energy, making it one of the most significant sources of environmental impact during the life cycle of wine [7,8]. Up to 30% of wine's carbon footprint comes from glass bottle production, by far the largest amount of carbon compared to any other part of the wine industry [5,9]. On the other hand, consumers, especially the young, Millennial and Gen-Z demographics, are increasingly aware of ethically conscious winemaking and are driven by sustainability and price. As a result, innovative technologies and changing consumer values are driving the modernisation of packaging options for the wine industry.

The 21st century has brought one of the most significant revelations in wine storage and transport history. Plastic, a cheap and lightweight material, is being used to create new wine bottles. Boxed wine is another innovation currently gaining momentum, where wine is packed in an airtight plastic bladder that emerges from a larger carton (bag-in-box systems [6]). Another innovative and challenging form of packaging in the wine industry is canned wine. It is expected that the use of lighter packaging alternatives will significantly reduce the environmental impact of the wine life cycle.

To explore the future of wine packaging, a robust theoretical foundation is essential, encompassing environmental sustainability, consumer behaviour, innovation, supply chain management, branding, corporate social responsibility (CSR), and cultural studies.

Within the context of ecological modernisation theory [10], the wine industry's transition toward sustainable packaging practices aligns seamlessly with the overarching goal of minimizing its ecological footprint. As we delve into consumer behaviour theories, such as the Theory of Planned Behaviour (TPB) [11,12] and the Diffusion of Innovation theory [13], we gain insights into how consumers perceive and adopt novel wine packaging formats. Understanding the interplay of attitudes, subjective norms, and perceived behavioural control aids in anticipating consumer acceptance and integration of innovative packaging solutions. Transitioning to innovation theories, particularly the Technology Adoption Model (TAM) and the Diffusion of Innovation framework [14], provides deeper insights into the adoption and diffusion of new packaging technologies within the wine industry. This understanding helps forecast the widespread acceptance of sustainable and innovative packaging solutions.

The future of wine packaging is intricately linked to supply chain dynamics. By leveraging supply chain sustainability theories and principles of the circular economy, we assess the broader impact of packaging choices on the entire wine production and distribution chain. Evaluating the life cycle of packaging materials identifies opportunities for sustainable practices at various stages of the supply chain. In the realm of branding and marketing theories, such as the Brand Equity Model [15,16] and the Extended Marketing Mix (7Ps) [17], we gain insights into how packaging shapes consumer perceptions. Packaging emerges as a pivotal element in the overall marketing strategy, influencing brand image and consumer loyalty. These theories provide a lens through which to understand the role of packaging in the consumer's overall wine experience. Shifting towards corporate responsibility, incorporating socially and environmentally responsible packaging aligns seamlessly with CSR theories [18]. By examining how wine companies integrate CSR principles into their packaging strategies, we assess the industry's commitment to ethical and sustainable practices. CSR theories guide our exploration of how packaging decisions contribute to positive societal impact, reflecting a broader commitment to responsible business practices.

Finally, cultural studies theories and lifestyle branding concepts play a crucial role in anticipating how cultural trends influence wine packaging preferences. Analysing the cultural capital associated with different packaging choices helps us understand consumer responses and expectations, shaping the cultural narrative surrounding wine consumption.

This study aims to explore the historical evolution of wine packaging, identify the environmental impacts of glass production, and examine emerging alternatives to assess their potential sustainability benefits. The research questions guiding this study revolve around understanding the historical context of wine packaging, identifying the environmental impacts of traditional glass bottles, and assessing the feasibility and sustainability implications of modern packaging alternatives, including plastic bottles, bag-in-box systems, and canned wine. Through this research, we aim to contribute to the ongoing discourse on sustainable practices within the wine industry, providing insights that align with evolving consumer values and innovative technologies.

2. Wine packaging options

2.1. Glass wine bottles

The first glass wine bottles were made by the alchemist and food writer Sir Kenelm Digby in Newnham-on-Severn, Gloucestershire, England, in the 1630s [19], and the glass wine bottle has been a traditional way of storing wine ever since.

The advantages of using glass bottles for packaging and storage are: i. Glass is non-toxic, odourless, and transparent, and provides an excellent barrier to prevent gases (e.g., oxygen) from entering the contents and also prevents the volatile components of the contents from escaping into the atmosphere; ii. A glass bottle can be reused, which can reduce packaging costs; and iii. A glass bottle is safe and hygienic, has excellent corrosion resistance to acids, and is, therefore, suitable for packaging acidic materials such as wine.

The disadvantages of glass packaging are: i. Glass is heavy and breaks easily. ii. It can be recycled, but the weight and shape of the bottle create a carbon footprint problem. iii. In addition, due to its weight, a glass bottle is difficult to carry on foot over long distances. The classic wine bottle, practically unchanged since the 17th century, is seen by many as a cherished tradition. However, it is difficult to reduce the efficiency of today's wine packaging. Sacrifices must be made in order to act decisively to achieve the sustainable wine trade that the planet needs. While environmentally friendly production methods and bottle shapes will undoubtedly contribute to a more sustainable wine industry, the most important thing that can be changed now is the materials used for wine packaging.

Burning fossil fuels as an energy source in the glass-melting process [6] results in unavoidable carbon emissions, while improvements in conventional technology have reached their efficiency limits. Switching to electric heating methods has many advantages, including better energy efficiency and reduced combustion-related emissions.

Glass has been melted for around 6000 years, and wood was the primary energy source for most of that time. More recently, around 1880, the industry began to use fossil fuels, including coal, oil, and natural gas. By this time, the regenerator had been invented to improve the efficiency of steel blast furnaces, and the glass industry soon adopted it for the early side furnaces, which are very similar to those of today. Fossil fuels have been used for less than 150 years in these millennia of glassmaking, and they may not be available for another 150 years. Although new fossil fuels have recently become available, the world has finally understood that burning them results in unavoidable carbon emissions, and this method must end. At this stage, glass must continue to be melted because we have not yet found a viable substitute. Therefore, the glass will likely be around for many centuries, and the inevitable future for a carbon-efficient glass industry will be all-electric. As with many other commodities, as soon as we think we are running out of resources, we find new ones. Fossil fuels are no different. So why should we even consider moving away from fossil fuels? Science has proven that CO_2 emissions are linked to global warming, likely leading to serious environmental problems for humanity. The European Union has committed to cutting the emission of greenhouse gases to 80% below 1990 levels by 2050. The milestones for achieving this target are emission reductions of 40% by 2030 and 60% by 2040. Legislation, customers, and common sense will sooner or later force the industry to move away from burning fossil fuels. All sectors must contribute. A well-known Dutch brewery is making significant efforts to reduce its carbon footprint and estimates that 53% comes from its packaging material. The demand to reduce emissions is coming from many sides. It will influence how glass is melted in the future, regardless of whether we agree with it. Even in the early days, the efficiency of all-electric melting furnaces was 1.3 MWh/tonne, close to today's most efficient fossil fuel-fired furnaces at 1.1 MWh/tonne. Since the introduction of all-electric furnaces, huge efficiency gains have been made, reducing energy consumption to 0.78 MWh/tonne or less. Electricity consumption is unlikely to fall below 0.72 MWh/tonne. Compared to conventional fossil fuel heating at 1.1 MWh/tonne, energy consumption is approximately 35% lower. Most of the electrical energy goes into the smelting process anyway, and there are relatively small energy losses occurring through transformers, busbars and control efficiency. All-electric furnaces are sophisticated but very simple in design compared to highly efficient fossil fuel-fired smelters. No regenerators or burner skids are required, and expensive high-temperature crowns are unnecessary. Higher throughputs are easily achieved. There are no combustion-related CO_2, thermal NO_x, or SO_x emissions. There is less evaporation of volatile and expensive raw materials such as boron, lithium, etc., making exhaust gas filtration much more manageable. The carry-over problem is also virtually eliminated, and smaller furnaces can be considered. Although the concepts for all-electric furnaces are generally straightforward, there are several issues to consider when converting to this technology. Glass or glass composites are electrical insulators at room temperature. The glass must pass through a preheating sequence to start the electric heating process, similar to container and float furnaces. An all-electric furnace also requires a stable, reliable power supply, and because of the different melting and refining behaviour, the glass composition needs to be changed. Electricity prices need to come down to reduce the carbon footprint. Instead of coal-fired power stations, electricity would have to come from renewable sources. Electrodes need to be maintained by developing them to increase resistance as they wear. There are new methods of counteracting electrode wear that would require further research. Another issue, particularly for the container industry, could be how this type of furnace would handle large amounts of cullet, leading to different cullet and batch handling.

Hydrogen and "green" furnaces are promising innovations in bottle manufacturing, particularly for glass. These technologies align with sustainability goals by reducing carbon emissions and energy consumption [20,21]. An overview of these furnace technologies and their potential impact on bottle production is presented in **Table 1**.

Table 1. Furnace technologies and their potential impact on bottle production [22].

Furnace type	**Hydrogen Furnaces**	**Green Furnaces**
Technology	Hydrogen furnaces use hydrogen gas as a clean fuel source for heating and melting glass raw materials.	Green furnaces are powered by renewable energy sources like solar, wind, or geothermal energy.
Advantages	1) Low Carbon Emissions: Hydrogen combustion produces only water vapor as a byproduct, resulting in minimal greenhouse gas emissions. 2) Energy Efficiency: Hydrogen combustion can be highly efficient, reducing energy consumption in the glass-melting process. 3) Sustainable Sourcing: Hydrogen can be produced from renewable sources, such as electrolysis using green electricity or by reforming biogas.	1) Zero Emissions: Energy from renewable sources produces no direct carbon emissions, contributing to a reduction in the carbon footprint of glass production. 2) Sustainable Energy Supply: Utilizing renewable energy aligns with sustainability goals and reduces dependence on fossil fuels. 3) Energy Cost Stability: Renewable energy sources can provide stable energy costs over time.
Challenges	1) Hydrogen Infrastructure: Widespread adoption may require investments in hydrogen production and distribution infrastructure. 2) Safety Measures: Handling and storing hydrogen safely are essential due to its flammability and potential for leakage.	1) Intermittency: Some renewable sources are intermittent, requiring energy storage solutions or backup systems. 2) Initial Investment: Implementing renewable energy systems may require substantial upfront investments.

The use of hydrogen furnaces and green furnaces in bottle production represents a shift towards more sustainable and environmentally friendly manufacturing processes. These technologies help reduce the carbon footprint associated with glass production, bringing it more in line with sustainability goals. However, the successful implementation of these technologies depends on several factors, including technological advances, energy infrastructure, cost effectiveness and regulatory support. Manufacturers in the bottle manufacturing industry are increasingly exploring these options as they strive to reduce their environmental impact and meet sustainability goals [23].

The glass industry, one of the largest energy consumers in a rapidly changing energy market, needs to look for furnace designs that better meet the needs of today and tomorrow [23]. Advanced data analytics and (model-based) control strategies should help operators calculate the available control margin and the allowable variations in melt energy and fossil/electric fuel ratios and predict the impact on glass quality. The conclusion is that nothing can be done without thinking “out of the box” and breaking with traditions.

2.2. Eco-friendly wine packaging

As glass recycling rates continue to increase, there has been a noticeable reduction in the emissions associated with the use of glass bottles. However, sensitivity analysis assessing the approximate carbon footprint of alternative packaging options has shown that a faster reduction in emissions can be achieved by switching to different packaging materials rather than relying solely on increased glass recycling efforts [24–26].

A significant reduction in the life cycle impact of wine can be achieved by replacing glass bottles with lighter packaging alternatives such as polyethylene terephthalate (PET) bottles, aseptic cartons and bag-in-box [27–30].

Polyethylene terephthalate, abbreviated PET, is the most commonly used thermoplastic polymer resin in the polyester family. PET consists of ethylene glycol and terephthalic acid, which combine to form a polymer chain [31]. The resulting PET material can be extruded, cooled and formed into small pellets. The pellets can be heated, allowing them to be easily extruded and moulded into different shapes [31]. PET bottles can be produced as single or multi-layer bottles. To maximise the gas barrier properties of PET bottles, it is recommended to use either a three or five-layer structure of PET/gas barrier resin/PET [32]. The permeability of gases through the packaging material depends on the crystalline polymer structure [33]. PET bottles have been widely used for food and beverages such as lemonade, juice and water for many years [31]. In addition to CO_2 barrier properties, PET bottles can protect sensitive products from sensory and nutritional deterioration due to oxidation. The barrier properties of PET can be improved by adding oxygen absorbers inside the bottle [34].

With the current emphasis on environmentally friendly packaging, plastic wine bottles are not as unusual as one might think. While glass bottles can also be recycled, plastic bottles are much lighter and have a much lower carbon footprint. For example, studies have shown that replacing one billion glass bottles with plastic bottles would save around 90,000 tonnes of carbon monoxide. PET bottles are inexpensive. They offer relatively good barrier protection against water, oxygen, and carbon dioxide. Their lighter weight reduces the environmental impact of transportation, and there is less product loss due to damage during filling and storage [31,35]. When comparing the average weight of PET bottles to glass, PET bottles weigh only 60g compared to 460g for glass [35]. The weight reduction can also reduce the shipping cost and carbon emissions by as much as 30% according to some estimates [36]. It is also worth mentioning that PET bottles can be recycled, but unlike glass, there is a limit. Over time, the structural integrity of the plastic is degraded, and it has to be made into something else [37].

As with so many things, all that glitters is not gold. Plastic bottles also have their drawbacks. Unlike glass bottles, plastic bottles allow oxygen to diffuse through them. Plastic bottles are filled with barrier technology and oxygen absorbers to avoid this problem. These chemicals are not harmful to the consumer, but many consumers believe otherwise. Even with barrier technology, plastic bottles allow more oxygen to enter the bottle than glass. This is why wine in plastic bottles has a shorter shelf life. In addition, some authors have highlighted several critical issues with plastic recycling, such as the difficulty of achieving closed-loop recycling [38] and the possible presence of contaminants in recycled plastic [39].

So, will plastic bottles replace glass wine bottles? Only time will tell, but plastic bottles will probably only be used for cheaper wines that are not intended to spend much time on the shelf or in the cellar.

Aseptic cartons and bag-in-box offer significant economic and logistical advantages. They cost less than glass bottles, making transport and storage more efficient [40]. As a result of these characteristics, aseptic cartons are now the most widely used packaging in the Chilean domestic market [40].

Bag-in-box packaging consists of a flexible, foldable, sealed double bag made of plastic film and a polypropylene (PP) valve inside a rigid outer carton or container to which a spout is attached for dispensing the wine. The outer bag is made of polyester to provide a higher barrier. The inner bag is either low-density polyethylene (LDPE) or ethylene vinyl acetate (EVA) [41]. Wine bags are filled under a vacuum with nitrogen to remove any remaining oxygen in the headspace. The bag begins to collapse when the wine is removed from the carton through the valve, protecting the wine from oxygen [41]. This type of packaging is typically used for medium-quality table wines. The most common sizes are three and five litres [42]. It should be noted that the physical strength of the bag is essential. The bag itself must be able to withstand the stresses of transport and subsequent storage. During transport, the bag itself is subjected to several different types of stress: (i) hydraulic shock (due to sudden acceleration/deceleration) and (ii) bending (due to the vibrations transmitted by the wine, which bends the bag). Due to the flexibility of this packaging material, fatigue occurs, leading to holes and consequent failure of the material. To solve this problem, polymer films with high flexural strength are used to increase the bond strength within the laminated webs. This ensures that the volume of the bag and box are close together, and a second bag is used for cushioning [43]. The vast majority of bag-in-box (BIB) packaging also contain an aluminium layer. The use of an aluminium layer in bag-in-box packaging is a common practice in the wine industry, primarily to prevent oxygen (O_2) from entering the package and spoiling the wine. The aluminium layer acts as an effective oxygen barrier, maintaining the freshness and quality of the wine for an extended period of time, even after the package has been opened. This technology has become a popular choice for both winemakers and consumers due to its convenience, environmental credentials, and ability to preserve the flavour and aroma of the wine.

A major problem with bag-in-box wine packaging is the reduced shelf life compared to traditional glass bottles [44]. In the 1970s, people in Australia noticed that their bag-in-box wine started to taste oxidised and had lower free SO_2 levels as early as three months after packaging. At that time, bag-in-box had an approximate shelf life of about six months. It was unclear whether the reduction in shelf life was due to the permeation of O_2 into the wine or SO_2 out of the wine. The researchers found that the permeation of SO_2 from the wine was negligible, but the real culprit causing the wine to spoil was the O_2 in the wine. The oxygen was able to penetrate through the valve and seal the bag. Based on these findings, the bag-in-box wines could be significantly improved. They are now produced with an O_2 barrier for the bag, spout, and closure. Today's bag-in-box design consists of a one-piece flexible valve that opens and closes when a lever is operated [43], keeping the wine fresh for two to three weeks after opening.

Bag-in-box remains one of the most popular non-glass packaging options for wine, with a market share of around 5% [45]. Consumers are attracted to the 3L size of the bag-in-box, equivalent to 4 standard-size bottles and can keep wine fresh for several weeks once opened. The bag-in-box is available in 1.5 litre and 500 ml Tetra Pak containers [45].

In 2010, BIB accounted for more than 50% of all wine purchases in Australia, Sweden and Norway, 20% in the UK and France and less than 18% in the US [46].

The idea for a tetrahedron-shaped, folded paper tube package for food and beverages, later known as Tetra Pak, dates back to 1944 [47]. Originally a subsidiary of Åkerlund & Rausing, Tetra Pak was founded in Lund, Sweden, and became an independent company in 1951. Since then, innovative packaging has expanded into many applications in the food and beverage industry, making Tetra Pak the world's most prominent food packaging company [48]. Tetra Pak is an aseptic, multi-layer carton made from three primary, separate materials: cardboard, polyethylene polymers, and aluminium [49]. Cardboard is the primary material within the package. It provides stability, strength, and a smooth, ink-receptive surface for label printing. Polyethylene polymers protect the product and packaging from external moisture from the environment and internal moisture from the product. These polymer layers also form a food-safe coating between the product and the packaging materials. The polymer layer also allows the carton to adhere to the aluminium foil, which protects the product from oxygen and light. This prevents photo-oxidative reactions [50]. Tetra Pak packages are available with different types of closures, but the most common closure for wine packaged in Tetra Pak is a plastic screw cap [51]. This plastic screw cap has barbs on the underside that cut through the protective layer and allows access to the product.

Wine packaging in Tetra Pak cartons was introduced in the early 1960s and the first wines in Tetra Pak cartons were primarily produced and sold in Europe. This packaging format offered an alternative to traditional glass bottles and proved convenient for single-serve and on-the-go consumption. Over the years, the use of Tetra Pak cartons for wine packaging has grown and they are now a common sight in various markets around the world, offering consumers a lightweight and environmentally friendly option for wine consumption.

Designed specifically for wine, the Tetra Pak Prisma offered a flexible package that allowed air to be squeezed out, reducing oxidation, extending shelf life, and providing an airtight seal with 100% UV protection [52]. Tetra Pak packaging offers wine producers a cost-effective alternative to traditional wine packaging, such as glass, as it costs only 10-25 cents to fill and produce a Tetra Pak package [53]. The flexible packaging is less prone to breakage, which reduces product loss and damage due to breakage. As Tetra Pak packaging is lighter than glass, the cost of transporting the product is also reduced.

2.3. Canned wine

The aluminium can is the most common solution to the weight and transport problems of glass. Canned wine is gaining popularity and acceptance among consumers, leading to significant growth in the market. In 2019, the market for canned wine expanded by 80%, reaching a value of $90 million. The advantage of canned wine is that it can be chilled more quickly. Furthermore, wine waste is reduced since there is no need to open an entire bottle, when a person wants to consume only a single serving of alcohol at a time. The small pack encourages tasting and provides consumers with a portable alternative when glass is not preferred, such as at events or outdoor activities. Sustainability is just one of the benefits of this format.

Canned wines are often appreciated for their low tannin content, high acidity and fruity profiles. They are also a better choice for people with sulphite allergies and those with active lifestyles [54,55]. A key benefit for those with sulphite allergies is the reduced use of sulphites in canned wines. These wines typically contain lower levels of added sulphites than their bottled counterparts. Sulphites are commonly used in winemaking as a preservative to prevent spoilage and oxidation. However, some people are sensitive or allergic to sulphites, which can cause adverse reactions such as headaches, hives or respiratory problems. Canned wine packaging, with its more airtight seal, requires fewer preservatives. Another benefit is reduced exposure to oxygen. Canned wines are sealed with airtight screw-top or pull-tab lids, minimising contact with oxygen. This preserves the freshness of the wine and reduces the need for excessive use of sulphites, as oxygen can affect wine quality. In addition, canned wines are often sold in single-serve portions, eliminating the need to leave the wine open for long periods of time. This minimises sulphite exposure as the wine is not exposed to oxygen. Portability and convenience are also important [55]. Canned wine is lightweight, easy to carry and perfect for people on the move. This convenience encourages on-the-go consumption and reduces the likelihood of wine being exposed to oxygen for long periods of time, thus requiring less sulphites for preservation. Finally, canned wine offers a diverse range of options, including red, white, rosé and sparkling varieties. This diversity allows people with sulphite allergies to explore different options and discover wines that are less likely to trigger sensitivities.

Commercial examples of canned wine date back to the 1930s, when cans were made from tinplate [56]. However, wine is now packaged in modern aluminium cans, which have only been in use for the last two decades [57]. Cans are made from three different materials: (1) aluminium, (2) tin-coated steel (tinplate), and (3) electrolytic chromium-coated steel (ECCS) [58]. Bare aluminium metal is highly reactive and can form an incredibly thin (nanometre) passivation layer of aluminium oxide when exposed to air or water. The aluminium oxide passivation layer has low reactivity, which is why aluminium foil and other aluminium-based products are considered relatively inert. More commonly, aluminium cans have a thin (1–10 mm) polymer coating on the inside of the can to protect against the high reactivity of bare aluminium. Without the protective inner polymer layer, the acidic pH of the wine could cause the interior of the can to slowly corrode. The consumer is unaware of the presence of the inner protective layer as it is invisible to the naked eye.

Unlike carbonated drinks, wine must be backflushed with N_2 to increase the internal pressure of the can. Otherwise, the can could collapse. The thin aluminium has inherently low internal strength; it relies on the pressure exerted by the beverage to keep it from collapsing. For a wine to be successfully packaged in cans, it must meet two requirements: (i) the nature and integrity of the lining of the inner wall of the can and (ii) a minimum O_2 concentration within the can at the time of filling [43]. The O_2 concentration should be as close to zero as possible to minimise oxidative reactions that lead to off-flavours [59].

For years, canned wine was not a category of choice, with many thinking it was a fad that would not last. However, the growth of canned wine in recent years means that it should now be considered. In less than a decade, canned wine sales have grown from $2 million in 2012 to more than $183.6 million in July 2020. This is equivalent to around 1.8 million cases of wine consumed last year [60]. Although canned wine only accounts for approximately one percent of the market, it is the fastest-growing alternative packaged wine sector [45]. Canned wine is booming on all fronts, from quality to distribution and availability [60]. Canned wine is already a big hit at sporting events, concerts, theme parks, and other outdoor events where glass bottles are banned [57,60]. Surprisingly, restaurants are also turning to canned wine [60].

The availability of canned products has made wine more accessible and attractive to a broader audience, including younger and older drinkers. While millennials initially drove growth in the canned wine category, others of all ages, including traditional wine drinkers and some beer drinkers, are attracted to canned wine. Wine is often thought of as only being served at fancy dinner parties in fancy glasses. Yet, canned wine has challenged this misconception and allowed people to experience wine wherever they are, such as at professional sporting events, barbecues, and tailgates. Initially, canned wine sales only increased in the spring and summer months as people began to enjoy the outdoors, but this is no longer the case. Sales have started to grow all year round [45].

One of the main challenges associated with canned wines is the development of reductive aromas [54]. These aromas typically result from the formation and release of hydrogen sulphide (H_2S), which, when present in significant concentrations, is characterised by its distinct 'rotten egg' or 'vegetal' odour. Even at low concentrations, H_2S can reduce the fruity character of the wine, leading to disappointed consumers. The development of reductive aromas in canned wine can occur anywhere from a few weeks to several months after packaging.

The development of reductive aromas in canned wine can be attributed to three primary mechanisms: the interaction of SO_2 with aluminium metal, the release of H_2S from metal-bound complexes present in the wine, and the degradation of polysulphanes [61].

The first mechanism is likely to be the main contributor to H_2S formation in canned wine. Under acidic conditions, sulphur dioxide (SO_2) interacts with aluminium to form hydrogen sulphide (H_2S) [62] (as shown in Equation (1)). It is important to clarify that the formation of H_2S results from the direct reaction between SO_2 and aluminium metal, rather than from dissolved aluminium ions in the wine. To facilitate this reaction, the SO_2 must be in direct contact with the aluminium metal. Proposed pathways for such contact include coating imperfections, coating degradation and the possible diffusion of wine components through the coating. The exact pathway remains unclear and is likely to vary in each situation due to numerous influencing factors.

$$2Al_{(s)} + SO_{2(aq)} + 6H^{+}_{(aq)} \rightarrow 2Al^{3+}_{(aq)} + H_2S_{(g)} + 2H_2O \qquad (1)$$

The release of hydrogen sulphide from metal-bound complexes and polysulphanes is not unique to canned wine and can occur with various packaging methods. The extent to which these pathways contribute to the release and accumulation of H_2S in canned wine remains uncertain [63]. In general, the release and buildup of H_2S are closely related to the presence of metals, particularly copper, in the wine. In addition, factors such as pH, the presence of reducing agents (such as sulphur dioxide and ascorbic acid) [61] and oxygen levels are important.

In bottled wine, oxygen can infiltrate through the closure, potentially mitigating some of the H_2S accumulation. However, in the oxygen-depleted environment within a sealed aluminium can (assuming low oxygen levels during sealing), the formation of H_2S by these mechanisms can be particularly pronounced.

One of the challenges with canned wines, especially when reducing the use of sulphites, is the potential for a shorter shelf life compared to bottled wines [54]. Here are some of the factors that contribute to this issue. Canned wine, like any packaged product, can be susceptible to oxygen ingress over time. Although cans provide a relatively airtight seal, they are not completely impermeable to oxygen. If oxygen enters the can, it can interact with the wine and cause oxidation, which negatively affects the taste and quality of the wine. Canned wines are generally intended for immediate consumption and not for ageing. Traditional bottled wines often benefit from aging, which can soften harsh tannins and develop complex flavours. Canned wines lack this aging potential. Cans can be more sensitive to temperature changes than glass bottles. Extreme temperature changes can cause cans to expand and contract, potentially compromising the seal and leading to wine quality issues. The materials used in can liners can affect the shelf life of the wine. Some liners may not provide an effective barrier against oxygen ingress, while others may be more suitable for preserving wine quality [64].

To address these challenges and extend the shelf life of canned wines, winemakers are exploring approaches such as: 1) Improved linings: winemakers are researching and developing advanced can linings that offer better protection against oxygen ingress and maintain wine quality. 2) Sulphites and antioxidants: while the aim is to reduce the use of sulphites, winemakers can still use minimal amounts to stabilise the wine. In addition, antioxidants such as ascorbic acid or vitamin C can reduce oxidation. 3) Packaging innovations: some canned wine producers are investing in packaging innovations, such as oxygen scavenging technologies, to further reduce oxygen exposure and extend shelf life. 4) Storage recommendations: wineries may provide specific storage recommendations for canned wines, including temperature ranges and avoiding extremes, to help consumers maximise wine quality over time.

Research efforts are currently underway to extend the shelf life of canned wines, with the aim of improving both their quality preservation and longevity on the market. These initiatives are driven by the growing demand for convenient and environmentally friendly packaging options, as well as the desire to ensure that consumers can enjoy wines in peak condition long after they have been purchased [65].

2.4. Latest inventions

In search of an environmentally friendly and easy-to-carry wine bottle, two French business school students developed a container that produces only 114 g of CO_2, compared to 502 g for a glass wine bottle [66]. It was called the “bio-teille”, which means “organic” and “bottle” in French. A “bio-teille” is a wine container made of moulded fibre into which a flexible bag compatible with recycling channels is inserted. The mouldable fibre, in turn, is a pulp obtained by mixing water with recycled fibres from old cardboard boxes and newspapers. It is shaped, pressed, and then dried at 180°C. This is how the shell of the Bio’teille is made. Interestingly, the cap is also made from this material [66].

Perhaps one of the most striking recent innovations in this field is the flat wine bottle created for Garçon Wines. Made from recyclable polyethylene terephthalate (PET), the bottle takes up 40% less space than a round bottle and is 87% lighter than a glass bottle [6]. To further enhance these benefits, the company has developed a 10-bottle case that reduces greenhouse gas emissions and business costs by 60%. The crate can hold 1,040 bottles when stacked on a pallet, compared to 456 for a conventional bottle. They are also more durable than glass bottles and can be reused.

3. Sustainability requirements for packaging

Packaging is essential for product delivery and protection, but it often generates significant amounts of waste and contributes to environmental degradation. Sustainability requirements for packaging refer to the set of criteria and guidelines that aim to minimise the environmental and social impacts of packaging materials and practices throughout their life cycle. Sustainable packaging addresses these issues by considering various factors such as recyclability, biodegradability, energy efficiency, water and carbon footprints, life cycle assessment (LCA), local sourcing, etc. Governments and industry organisations in many regions have established regulations and guidelines to promote sustainable packaging practices. Companies are increasingly recognising the importance of sustainable packaging, driven not only by environmental concerns but also in response to consumer preferences for environmentally friendly products. Ultimately, sustainable packaging aims to balance the practical requirements of packaging, economic considerations and the need to protect the planet’s resources for future generations.

A comprehensive overview of the main sustainability requirements and the corresponding strategies for addressing them in different types of wine packaging is presented in the Supplementary Material section and summarised in detail in **Table S1**.

In addition, a table summarising the waste management, recycling challenges and degradation concerns for different types of wine packaging has been presented in the Supplementary Material section in **Table S2**.

To address the environmental challenges associated with wine packaging, the wine industry is actively pursuing several strategies to improve sustainability. One approach is lightweighting, a practice aimed at reducing the weight of packaging materials to minimise carbon emissions during transportation. At the same time, there is a strong focus on recycling education, with initiatives aimed at raising awareness and promoting good recycling practices among both consumers and industry stakeholders. Material innovation is another key facet, as the industry invests in researching and adopting alternative, more sustainable packaging materials. In addition, the adoption of circular economy practices plays a crucial role, involving the implementation of principles that prioritise material reuse and recycling. Ultimately, a comprehensive and holistic approach is seen as essential, with industry professionals, consumers and policy makers working together to develop and implement sustainable practices throughout the life cycle of wine packaging.

Glass as a material is generally inert and does not release toxic substances that would have a negative impact on ecosystems in its typical use, such as in the form of glass bottles or containers. Glass is mainly composed of silicon dioxide molecules (silica), a naturally occurring and non-toxic substance [67].

Plastic poses environmental challenges through the release of toxic substances throughout its lifecycle [68]. Chemical leaching from plastics containing compounds such as bisphenol A and phthalates can disrupt the endocrine systems of wildlife, leading to reproductive and developmental problems [69]. Microplastics, which result from the degradation of plastic items, absorb and transport environmental contaminants, posing a threat to aquatic ecosystems and wildlife through ingestion and bioaccumulation [69]. Certain plastics attract persistent organic pollutants such as polychlorinated biphenyls (PCBs) and dioxins, which further contribute to adverse effects on organisms. Improper disposal and accumulation of plastic waste disrupts habitats and alters natural processes in aquatic and terrestrial environments. In addition, plastics can release toxic gases when incinerated, contributing to air pollution. Addressing these negative impacts requires sustainable practices, including reducing single-use plastics, improving waste management and promoting environmentally friendly alternatives to mitigate the impact of plastics on ecosystems [68].

The environmental impact of bag-in-box packaging, made from materials such as cardboard and plastic, is primarily due to resource-intensive production processes and potential waste issues. While the paperboard is biodegradable, the plastic components can be persistent if not disposed of properly [68]. Recycling challenges arise from the combination of materials, which require specialised facilities. In addition, the inks and adhesives used to print the packaging may contain chemicals that could raise environmental concerns if not managed properly. Despite its potential benefits, such as reduced transportation costs, the overall sustainability of bag-in-box packaging depends on factors such as material composition, production practices and effective end-of-life management. Adherence to sustainable practices, including proper recycling and waste disposal, is essential to mitigate potential negative impacts on ecosystems [68].

While cans, usually made of aluminium or steel, are generally inert and do not release toxic substances into their contents, the environmental impacts associated with cans are largely related to their production and disposal processes. The mining and extraction of bauxite for aluminium production can lead to habitat disturbance and deforestation, affecting ecosystems [70]. In addition, energy-intensive aluminium production contributes to carbon emissions and environmental degradation. Efficient recycling practices are essential to minimise the environmental footprint of aluminium cans, as recycling requires significantly less energy than producing aluminium from raw materials. However, improper disposal or inadequate recycling can contribute to the accumulation of metal waste that poses a physical threat to wildlife and ecosystems. Coatings on cans, which are intended to provide protection, may contain chemicals that could pose risks if not properly managed. Despite these considerations, aluminium cans are often perceived as more environmentally friendly due to their high recyclability and lower weight, which reduces transport emissions. Responsible mining practices, energy efficient manufacturing, widespread recycling efforts and proper waste management are critical to mitigating potential negative impacts on ecosystems.

4. Factors influencing changes in wine packaging

Packaging changes are influenced by a number of factors, including cost considerations and consumer trends. According to the 2023 Wine Business Monthly Packaging Survey in the US, a significant 8% increase in the average cost of glass has led 43% of wineries to prioritise cost control in their packaging strategy [71].

Approximately 31% of US wineries have switched to lighter glass bottles to address this issue, primarily due to reduced emissions, lower bottle costs and reduced transportation costs. However, the concern that the switch will diminish the perceived premium quality of the brand remains a significant barrier. On another front, health and wellness movements are shaping packaging trends as consumers, particularly in Australia, the UK, the US and Canada, look for packaging that encourages moderation in alcohol consumption. Wine Intelligence reports a growing awareness of non-traditional packaging types, with pouch containers gaining traction in Australia and the UK, and small single-serve bottles in Canada, particularly in 2022 [71].

An examination of off-trade wine sales by pack size in key markets (Australia, UK, US and Canada) shows the dominance of the standard 750 ml bottle as the most commonly purchased pack size, albeit with varying market shares. In particular, the 750 ml bottle has a significant volume share of 91% in the UK wine market, whereas in the US its volume share is comparatively lower at 5%. Contrasting market dynamics show that almost all other formats have a higher market share in the US, with the exception of larger casks, which are more popular in Australia and Canada. The one-litre format has a significant share of the Canadian market but has minimal sales in the other countries. Among the smaller formats, the 187 ml single-serve bottle is favoured in the UK, US and Australia.

Despite an overall decline in total wine sales in all four markets in the year to March 2023, certain forms of alternative packaging experienced growth. In Australia and the UK, both larger and smaller formats saw volume and value growth. For example, 5-litre kegs flourished in Australia, while magnums (1.5-litre bottles) and 3-litre kegs drove growth in the UK. Notably, the 187 ml bottle also grew in both markets, albeit from a lower base. In North America, the 500 ml format, mainly mini-barrels/tetra-packs, grew in the US, while the 375 ml format grew in Canada.

Over the past decade, the average annual volume of Australian wine exports has declined by 1%, while at the same time bulk wine exports destined for market packaging have grown steadily at an average rate of 1% per annum. This shift is evident in the transition from a volume share of 53% in the year ending June 2013 to a significant 69% share in 2023. As previously discussed, this trend towards alternative packaging methods, such as bulk containers, is motivated by a confluence of economic and environmental considerations. Opting for bulk containers allows companies to transport larger volumes of wine at a reduced weight, which translates into lower shipping costs, making it an economically and environmentally beneficial choice for exporters [71].

There is limited literature exploring consumer attitudes towards sustainability aspects of wine packaging, particularly beyond glass bottles. Ferrara and De Feo [72] conducted an exploratory study with Italian consumers and found that those who were less engaged and consumed less were more likely to accept alternatives such as bag-in-box (BIB) and cartons. However, even at lower prices, corked bottles remained the only acceptable form for more traditional consumers [6]. Barber [73] surveyed US consumers on their willingness to pay more for greener packaging, with around a third expressing a positive intention, driven primarily by high levels of environmental motivation. Given the strong association between bottle weight and perceived quality, reducing glass mass is a consumer-driven challenge for the dominant 750 ml glass bottle. Studies by Sáenz-Navajas et al. [74] and Ferrara and De Feo [72] highlighted the positive correlation between heavy bottles and perceived quality, even among consumers with greater knowledge of alternative attributes. At the premium end, wines associated with luxury and exclusivity are resistant to lighter bottles, as weight is intrinsic to their premium identity [75]. This is in line with trends in other premium liquid products, such as spirits and premium olive oils [76]. Sustainability efforts in premium packaging are gaining traction, as evidenced by initiatives at LuxePack, a major luxury packaging trade show [77]. In the wine sector, influential journalists are advocating for a reduction in the excessive weight of bottles used by premium producers, reflecting a growing awareness of sustainability concerns [78].

The biggest challenge to the future success of the wine industry is the shift in consumer ideology between the Baby Boomer, Generation X, Millennial, Generation Z and Alpha generations (**Figure 1**). The Baby Boomer generation is between the ages of 57 and 75 and is retiring. Not to be forgotten is Generation X, aged between 38 and 53. The generation that came after the Millennials and before the Alpha Generation is known as Generation Z, or Gen Z for short. They are also known as Zoomers. Researchers and media use the middle to late 1990s as the beginning and end of their birth years. As the first social generation to have internet access and portable digital devices from a young age, members of Generation Z have been described as 'digital natives', although they are not necessarily digitally literate. The majority of Generation Z are children of Generation X. In addition, adolescents are more susceptible to the negative effects of screen time than younger children. Generation Z is the first social generation to access the internet and portable digital technology from a young age, has lower teenage pregnancy rates, and is less likely to drink alcohol. Gen Z teens are better at delaying gratification than their 1960s counterparts and are more concerned with academic achievement and career prospects than older generations. In addition, Generation Z teens and young adults have a higher prevalence of allergies than the general population.

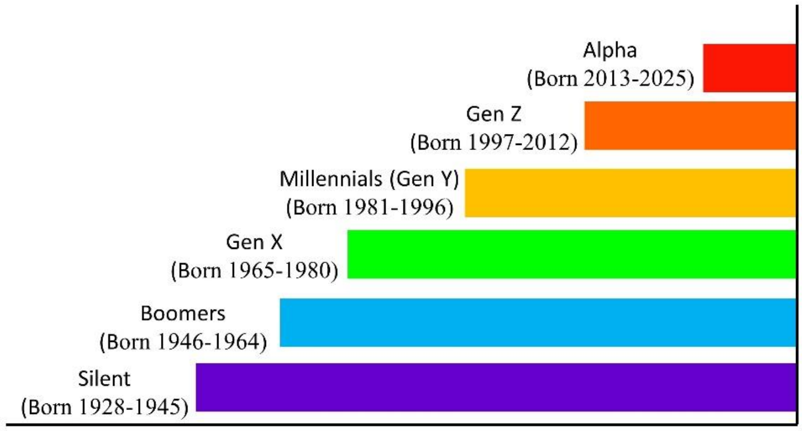

Figure 1. Generation by birth year.

The average wine consumer will change dramatically over the next decade. Wineries will have to work hard and be clever to retain the old generation of customers and attract new ones.

Even before quarantine changed all our lives, the wine industry recognised the need for revolutionary wine packaging concepts to appeal to millennial consumers. The wine industry has also learnt that millennials often appreciate wine in single-serve packaging with calories, carbohydrates, and other nutritional information on the label. This label also needs to be Instagram-friendly [79]. **Figure 2** shows Instagram friendly wine packaging.

Another key phenomenon of 21st-century living is the increasing number of single-person households, which is driving demand for products packaged in smaller portions. In line with the move to single person living, more consumers, especially younger age groups, tend to shop more frequently and in smaller quantities. The 21st-century consumer is less brand loyal. This simulates an interest in customised or versioned packaging and packaging solutions that can influence them. This also aligns with the desire for integrated marketing, with packaging providing a gateway to social media.

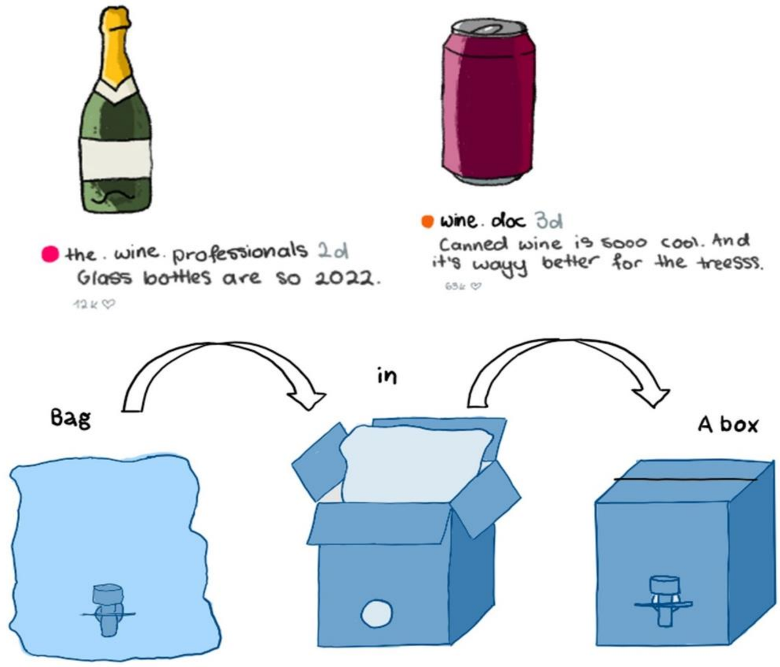

Figure 2. Examples of Instagram friendly wine packaging (@bestofwinepackaging).

5. Conclusion

The evolving landscape of wine consumption reflects dynamic lifestyles, with an increasing demand for portability and convenience in unconventional settings. Traditional glass packaging, restricted in many locations, hinders the desire to enjoy wine on beaches, parks, or poolside. Alternative packaging solutions, such as cans and plastic bottles, address this need for portability and appeal to consumers seeking lightweight and easy-to-carry options.

A notable aspect of these alternatives is their alignment with the demand for single-serve options, particularly favoured by the environmentally conscious younger generation. The awareness of the significant carbon footprint associated with glass bottle production has shifted consumer behaviour, leading to a trend towards sustainable and environmentally friendly packaging. This study highlights the comparative advantage of lower carbon emissions compared to plastic bottles or aluminium cans, influencing consumer choices.

While shedding light on evolving wine packaging preferences, it's crucial to acknowledge study limitations. The complex interplay of consumer behavior, industry practices, and environmental impacts necessitates ongoing research and nuanced analysis. Recognizing these inherent limitations is essential as we delve into the multifaceted landscape of wine packaging.

The study underscores the emergence of environmental and sustainability policy implications as a critical consideration. Consumer demand for sustainable packaging presents an opportunity for policy intervention aimed at promoting and incentivizing environmentally friendly practices within the wine industry. Policymakers can collaborate with industry leaders to create frameworks that incentivize and reward sustainable practices, facilitating a collective approach to achieving shared environmental goals.

Leading beverage companies are at the forefront of embracing sustainable practices, with ongoing technological advances offering promising avenues for further improvement. Acknowledging the progress made, policymakers can work alongside industry leaders to develop frameworks that incentivize sustainable practices, fostering a collaborative approach to achieving shared environmental goals.

In conclusion, the evolving landscape of wine packaging not only reflects changing consumer preferences but also presents an opportunity for policymakers to catalyze positive change. While this study has its limitations, future research efforts should delve deeper into the complex dynamics of wine packaging for a more comprehensive understanding of environmental, social, and economic impacts. Through collaborative efforts between industry stakeholders and policymakers, we can pave the way for a more sustainable and environmentally conscious future in the world of wine packaging.

Supplementary materials: Supplementary material to this review paper can be found online. References [80–85] are cited in the supplementary materials.

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