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Review

Developing a Sustainability Vision for the Global Wine Industry

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Abstract: Interest in sustainability has increased significantly in the wine sector in the past few years, driven by customer interest, as well as the impact of global warming-intensified weather extremes on wine growers. For a sustainable future the wine industry must design its entire value chain in such ways that it conserves and regenerates the natural environment and at the same time promotes human rights, inclusion and equality. The current paper identified five key challenges which have to be overcome in order to reach this goal: (1) climate change impact and adaptation strategies, (2) the reduction of GHG emissions and creation of carbon sinks, (3) vineyard inputs, (4) packaging and (5) social and economic sustainability. For each of these five challenges research gaps and possible solutions are presented which enable a holistic improvement of the sustainability of the whole wine value chain from the vineyard to the consumers. Examples for this are strategies to reduce the use of pesticides in the vineyard as well as carbon insetting options in the vineyard. Additionally, it is of utmost importance that every educational institution integrates facts and vision into their teaching programs in a holistic manner. Together, these approaches form the basis for a realistic sustainability vision for the global wine industry.

Keywords: sustainable wine industry; viticulture; climate adaptation; carbon neutrality; environmental performance; economic sustainability; climate change; education for sustainable development

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1. Introduction

Intensifying effects of the accelerating global warming press the need for transformative changes in our socio-economic global production and consumption patterns in order to avoid disastrous consequences for humanity. Rockström et al. (2009) [1] proposed nine planetary boundaries, which defined environmental limits for a safe operating space for humanity. In 2022 already five of these nine planetary boundaries were exceeded [2]. In particular, the exceedance of the planetary boundaries *climate change* and *biosphere integrity* bear a significant risk, as both are defined by Steffen et al. (2015) [3] as core boundaries due to their importance for the Earth system. One major driver of the exceedance of the planetary boundaries is humanities' management of agroecosystems [4] such as viticulture. Hence, there is increasing external and internal pressure on the agricultural sector to holistically improve its sustainability and to reduce its negative impacts on the environment.

This also applies to the wine and grape industry which is an economically important agricultural sector for several countries worldwide. According to the International Organisation of Vine and Wine, the global vineyard surface area amounted to around 7.3 million ha in the year 2021 [5] and the wine market revenue alone was estimated at USD 307 billion [6]. The past few years have seen a significant increase in interest in sustainability in the wine sector, driven by customer interest, as well as the impact of global warming-intensified weather extremes on wine growers. The challenge, however, is that the wine industry is a highly disaggregated sector, with the result that the sheer range and diversity of sustainability approaches risk confusion rather than coherent action. This is perhaps best reflected in the number of sustainability standards which have emerged in recent years.

What then has prompted this rise in interest in sustainability? After all, other sectors, such as textiles, cocoa, palm oil and coffee have long track records of addressing these issues. A survey undertaken of its members by the Sustainable Wine Roundtable (SWR) in May 2022, which consists of more than 70 organizations from industry and science along the entire wine value chain, identified a range of motivations [7]. Some of these are internal: companies see sustainability as "the right thing to do", while others also want to be a "better" company, not necessarily just in an ethical sense but "better" in the sense of always striving to improve practice and performance. Many organizations are facing specific, local sustainability challenges, be that pressure on water supplies, labor rights and working conditions, the need to manage relations with local communities or pressure to reduce chemical inputs. Others are engaging in improved sustainability practices to respond to pressures from their onward supply chain. Vineyards and wineries respond to increasing attention on their social and environmental practices from their buyers, who in turn are increasing their attention to these issues due to pressure from consumers and investors in wineries, vineyards and other wine-related businesses [8,9]. All are aware that scrutiny of sustainability will continue to increase over time in response to, for example, the EU's supply chain due diligence regulations which are due to come into force shortly [10].

In order to form a basis for a realistic sustainability future vision for the global wine industry, members of the SWR identified five key challenges for holistically improving the sustainability of the whole wine value chain from the vineyard to the consumers: (1) climate change impact and adaptation strategies, (2) the reduction of GHG emissions and creation of carbon sinks, (3) vineyard inputs, (4) packaging and (5) social and economic sustainability issues. In the following study the main sustainability challenges in these subject areas are described and possible solutions are discussed. In addition, research gaps are highlighted. In the context of this study emphasis is placed on the holistic understanding of the term "sustainability", which encompasses social, environmental and an economic dimensions [11]. These three dimensions cannot be considered independently of each other. Therefore, a key outcome of the current study is the discussion of interactions between the individual dimensions and the identification of possible negative trade-offs.

2. Global Warming Impacts and Adaptation Strategies

2.1. Global Warming Impacts on Viticulture

Grapevines are cultivated on six out of seven continents. The globally observed increase in temperature in almost all viticulture regions for at least four to five decades [12–16] has extended the range of cultivation to latitudes 4° and approximately 57° in the Northern Hemisphere and to 6° and approximately 46° in the Southern Hemisphere. This range encompasses a large diversity of climates (oceanic, warm oceanic, transition temperate, continental, cold continental, Mediterranean, subtropical, attenuated tropical and arid climates) [16–20]. Accordingly, the range and magnitude of environmental factors differ considerably from region to region and so do the principal environmental constraints for grape production [21].

The nature, number and extent of environmental constraints are currently changing due to shifts in climate patterns already observed in the past. The recently published 6th assessment report of the IPCC [22] shows case-dependent further expected shifts in climate patterns which will have substantial impacts on the way we will conduct viticulture in the decades to come.

Within existing production areas, where temperature conditions are generally favorable for grape cultivation, water shortage (extended, recurring, occasional) is probably the most dominant environmental limitation [23]. Water availability is a key factor for quality formation (positive and negative) [24–29] and water limitations are primarily associated with yield losses [30]. Climate change effects on the terrestrial water cycle show regional differentiated patterns. For example, soil moisture has decreased across Europe since the beginning of the 20th century [31], while regions in California and Australia largely depend on El Niño and La Niña weather patterns to determine dry and moist years [22]. In general, precipitation patterns are slowly but irregularly shifting with a trend to more uneven and extreme precipitation events. In addition, a concomitant increase in potential evapotranspiration (atmospheric water demand as a function of increased temperatures, ET_0) is observed in many wine regions across the world [22,24,32,33]. The latter phenomena are causing increasing events of soil erosion and associated carbon losses [34] and more droughts at the same time. With temperature, precipitation pattern and ET_0 being the drivers of change, a shift in regional suitability of wine regions [16,35,36] may result in the loss of their varietal "identity" due to altered phenology [13,37–39] and fruit composition [24,25,28,36,40]. This possible loss in varietal identity and the propensity of increased disease pressure [41] are main concerns and require adaptive measures to make viticultural systems more sustainable [42].

Taking all aspects together with a view on wine quality, the questions are whether we are already at the tipping point (in analogy to the planetary boundaries) [40,43] and what kind of adaptation measures could improve the sustainability of the wine industry?

Adaptation practices to changing environmental conditions should include:

1. Soil and water management: This has the highest priority in many areas and includes better infrastructures for water storage and distribution (specifically in previously unirrigated regions) [24], improved cultivation practices for water conservation such as soil organic matter (on average, 1% increase in C content increases water storage capacity by 16 L/m^2) [44], less intense tillage [42,45], altered canopy systems with reduced surface to volume ratios [46], increased trunk height to reduce temperature summation [24] or altered row distance to reduce water consumption [47]. Drought-tolerant rootstocks and varieties are also adaptive measures, as are reduced yields (price and consumer acceptance) to improve vineyard water relations [16,24,48].
2. Ripening delay: In order to move grape ripening back to cooler months, options are ranging from choosing higher elevation sites [49], altered trellising systems, delayed pruning, increased crop charges (where water permits), late ripening-inducing rootstocks, varieties and clones or specific interventions in canopy management [24,39,48,50,51]. Crop load management in conjunction with the irrigation regime can help to delay ripening and positively modify fruit composition [52].
3. Heat wave response: Heat stress and damage due to sunburn have increased over the past decades and can negatively alter grape composition [53,54]. Adaptive responses can include canopy system modifications, adapted timing and severity of leaf removal practices and improved water management [40,51,55].
4. Biodiversity: Grapevine biodiversity losses based on the reduction to a few varieties for the vast majority of global production is increasing the hazard of severe cli-

mate change repercussions [56]. Thus, the within-crop diversity should be increased through different cultivars.

In conclusion, the production challenges are vastly different from region to region, from product to product (i.e., sparkling versus still wine) or between red and white varieties and the strategies to ensure a sustainable product need to be adapted accordingly. The economic impact of these changes is difficult to assess but an in-depth analysis is necessary to construct relevant scenarios and risk analysis for individual regions and to quantify the costs and/or benefits of regional climate developments and the necessary adaptations.

2.2. Improving Climate Adaptation and Sustainability of Viticulture via Grapevine Breeding

As shown in the previous subsection, global warming and environmental degradation pose major threats for viticulture [18,57,58]. A key avenue towards putting the wine industry on a more sustainable path, that is aligned with the ambitious goals of the European Green Deal, is the genetic improvement of resource-efficiency and climate adaptation of grapevine cultivars.

Like many fruit crops, grapevine is a perennial grafted plant. This means that in the majority of vineyards, common grapevine (*Vitis vinifera* L.) varieties are grafted on rootstock varieties that are typically derived from either pure North American *Vitis* ssp. or from hybrids between these species [59]. Grafting was and still is the only effective way to control soilborne pathogens, such as phylloxera which destroyed most of the European vineyards in a major epidemic in the 19th century [60].

With regard to genetic improvement of grapevine, there are three key areas that breeding focusses on: rootstock breeding, cross-breeding for new scion varieties and clonal selection to improve traditional cultivars. Besides the advantage of biological pest control, rootstocks improve the vine's tolerance to abiotic stresses including drought, salinity or high soil pH levels [61]. The key to successful vineyard establishment is therefore the right choice of both the rootstock and scion variety [60,62]. Due to climate change, a high adaptability to drought of rootstock cultivars is becoming increasingly important [63].

Many American *Vitis* ssp. from which commercial rootstocks have been derived have evolved in regions with high disease pressure and various abiotic stresses such as drought and salinity. They therefore show high resistances/tolerances against those stresses. Rootstock breeding seeks to systematically explore natural variation for stress response via targeted hybridization through cross-breeding. Breeding new rootstocks by conventional methods is an extremely slow and high-effort process that can take 25–30 years or more [62,64,65]. Even though there are commercial rootstock varieties with good drought tolerance, the genetic diversity of available cultivars is extremely limited.

Only about half a dozen rootstock varieties make up more than 60% of the total growing area worldwide [62]. This gives growers a very limited range of suitable cultivars to choose from and increases the risk of novel disease outbreaks. Therefore, there is a strong need to develop new genetically improved rootstock cultivars that perform well under increasingly harsh climatic conditions [66,67].

Given the forecasted environmental shifts and the increased demands for more robust, stress-resilient rootstock varieties, conventional breeding methods are unlikely to deliver the required genetic gains fast enough. Modern molecular breeding tools such as genomic selection that incorporate genomic information in the breeding and selection process offer great opportunities for a more targeted and more rapid design of new rootstock varieties [68]. To explore their full potential, the links between molecular and phenotypic variation need to be understood [69]. Therefore, increased efforts to improve our understanding of the genetics underlying root development in grapevine are needed.

Developing new scion cultivars via targeted hybridization requires the adoption of new varieties that lack traditional fruit characteristics and regional wine identities which could be extremely disruptive to the industry. Most important grapevine cultivars are very old and have been vegetatively propagated for centuries [70]. In major varieties such as Riesling, which is over 600 years old, or Pinot Noir, which may be as old as 2000 years, this has led to large amounts of phenotypic variation for traits that are important for viticulture [71], e.g., yield, juice quality parameters or ripening behavior (Figure 1).

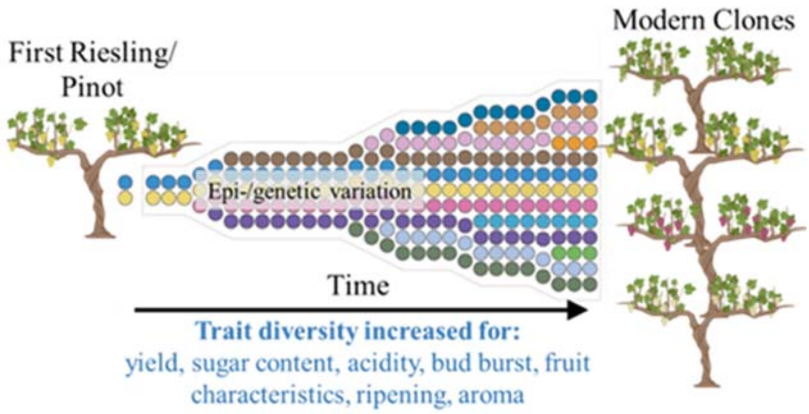

Figure 1. Vegetative propagation of grapevine varieties for hundreds of years has caused huge diversity for key traits.

Traditionally, breeding has explored intravarietal variation via targeted selection of new clones with improved traits that spontaneously appear in the vineyard [72], e.g., clones with looser bunch architecture that are less prone to grey mold infection. The major limitations of conventional clonal selection for grapevine improvement are that it (i) relies on spontaneous new variants with favorable trait characteristics and (ii) the ability to reliably detect them in the field. Furthermore, this process takes at least 20 years [72] which is too slow to meet the serious challenges viticulture is facing such as the accelerating pace of global heating. Therefore, novel precision breeding approaches that are capable of rapidly identifying, selecting and inducing new favorable alleles in traditional varieties are urgently required.

Cross-breeding for the generation of new scion cultivars represents another avenue for the genetic improvement of grapevine. The primary goal is to overcome the generally high levels of susceptibility of traditional varieties to biotic stresses, such as powdery or downy mildew, via targeted introgression of genetic resistances against these diseases from diverse donors, mostly other species of the *Vitis* genus, into elite *V. vinifera* genetic backgrounds. This practice has yielded substantial improvements in levels of genetic disease resistances which ultimately enable a significant reduction in the use of chemical plant protection. However, new varieties can lack traditional varietal characteristics which is why their adoption in the industry and consumer uptake have been relatively slow.

2.3. Outlook: Global Warming Impacts and Adaptation Strategies

The impact of global warming is one of the major challenges for the wine industry. Besides increases in global temperatures, the water availability is especially critical as it has an influence on both the yield as well as the quality of the grapes and thus also that of the wine. In particular, adjustments in the soil and water management can help vineyard operators in adapting to these changes in the environmental conditions. However, more research is necessary in order to analyze how the global warming impacts vineyards in different growing regions and which management techniques can help in the adaptation process.

Besides changes in the vineyard management, the breeding of new varieties is especially key for adapting to global warming impacts and for increasing the sustainability of the global wine value chain. A strong focus should be on the application of novel precision breeding approaches as they deliver results significantly faster as the traditional techniques.

3. Greenhouse Gas Emissions and C Sinks—On the Road to Carbon Neutrality

Global warming has, as shown in Section 2, a considerable impact on the wine value chain and especially on viticulture. However, the wine industry is not only a casualty of climate change, but also an important polluter. Therefore, in the following section, first the carbon footprint of wine value chains is analyzed and major hot spots are identified. Furthermore, mitigation options involving carbon (C) sinks for either reliable CO_2 compensation or C sink certification, accounting and trading in viticulture are discussed.

3.1. The Carbon Footprint of Wine Value Chains

Various studies assessed the carbon footprint of wine production, focusing on vineyards, wineries or the whole wine value chain (see, for example, [73–76]). The absolute results vary considerably between the various studies. They range from 0.68 [77] to 3.22 kg CO_2 eq. per 0.75 L of wine [78]. These variations are due to differences in the selected system boundaries, the methodological choices made and the assumptions applied, for example, in regard to the application of inputs, harvest yields, agricultural management practices or data quality [79,80]. However, regardless of the differences in the absolute results, the identified hot spots are quite similar across various studies. In vineyards, the most important sources of GHG emissions are the combustion of diesel in agricultural machinery and the production and application of (mineral) fertilizers and pesticides [80]. The winery phase, though, has the greatest influence on the carbon footprint of wine. Here, besides the thermal and electrical energy consumption, the production of the glass bottle, which is responsible for almost half of the total carbon footprint of one bottle of wine, is especially a major hot spot [81]. In addition to the emissions caused by the production process, the glass bottle also has a significant impact on the GHG emissions associated with the transport of the final product, due to its considerable packaging weight. This impact becomes more relevant when GHG-intensive freight modes are used or the wine has to be transported over long distances [82]. Ponstein et al. (2019b) [76] showed that a reduction in bottle weight or a reuse of glass bottles offers the chance to considerably reduce the carbon footprint of wine. The reuse of lightweight bottles led to a carbon footprint mitigation potential of 38% [76] and the use of new packaging types, such as bag-in-box solutions, was able to reduce the carbon footprint even further [83].

In summary, in order to reduce the carbon footprint of wine, the wine industry has to considerably decrease the inputs needed in the vineyard phase, increase the share of renewable energies and switch to low-carbon packaging solutions. However, even if all these mitigation options are applied, there are still significant carbon emissions during the wine production process that cannot be avoided. Therefore, potential additional mitigation measures including carbon sinks along the wine value chain have to be identified and developed, in order to reach a carbon-neutral viticulture [84].

3.2. Mitigation Options to Reach Carbon Neutrality

Viticulture offers several options to mitigate greenhouse gas (GHG) emissions or even to remove CO_2 from the atmosphere (carbon dioxide removal, CDR); the latter allows the inclusion of C-sink accounting and trade as part of vine estate management and economy. Mitigation measures can increase the overall sustainability and provide at the same time adaptation to global warming challenges and hazards. Measures that can actively reduce a wine estate's CO_2 footprint include (1) vineyard-based renewable energy production, e.g., by implementing agri-photovoltaic (agrivoltaic) systems in vineyards, and (2) carbon dioxide removal measures by changes in vineyard landscapes and their management.

Agrivoltaic (or APV) systems combine the production of crop yields with the generation of solar energy above the crop canopy on the same area of land [85]. APV systems mostly employ semi-transparent photovoltaic modules when inclined horizontally above the crop canopy (at heights that still allow machinery management) [86]. Vertical agrivoltaic systems, comparable to hedgerows, vine rows or fences, are mostly installed in meadows but they may be an interesting option for viticulture as well, since wind-breaking hedgerows can have water-conserving effects in vineyards [87]. However, there is still a huge need for research on the best beneficial implementation pathways of different APV systems in vineyards, with "unknowns" ranging from grapevine eco-physiological responses and microclimatic, phytopathological and soil-water-conserving effects to overall vine estate economics and economic dependence on novel regulations and green energy supporting frameworks. Geisenheim University built the first German APV research facility in 2022/2023 for viticulture-relevant research and invites researchers to join the living lab. Through the substitution of fossil energy sources, an APV system can mitigate significant amounts of GHG emissions. A study by Wagner et al. (2023) showed that APV systems have the potential to reduce the climate change impact by 572.94 t CO_2-eq ha^{-1} yr^{-1} [88]. Besides delivering green electricity for wine estates, APV systems may provide (a) added vine-growing benefits and (b) deliver an essential building block and catalyst to increase the sustainability of viticulture, e.g., by employment of robotics.

Towards vine-growing benefits, it is hypothesized that, based on current knowledge [85,89], agri-PV in viticulture will (i) preserve soil water by its diffuse shading due to reduced evapotranspiration; (ii) reduce the damage that late frost events can cause, either passively by reducing long-wave soil heat emittance or actively by providing electricity for heat cables or ventilators that can vertically mix cold ground air and warmer air 2–3 m above it; (iii) protect against the impact of extreme weather events, e.g., hail storms; (iv) reduce the amount of fungicide use by keeping vine canopies drier under the solar panels (i.e., fewer fungal infections); and, finally, APV shading will likely (v) slow down phenology and thus the process of grape ripening, which may help to preserve the typicity of, e.g., cool-climate cultivar wines such as Riesling under accelerating global warming conditions.

Towards the second point, providing on-site electricity for autonomous robots for vineyard management such as understock weeding, rolo-jacking or mowing can replace fossil-fuel-driven machinery, reduce associated CO_2 emissions and the use of herbicides and it may reduce soil compaction (which in turn improves soil water infiltration during heavy rainfall events).

Thus, the benefits of agri-PV systems in viticulture—in particular in low-precipitation rapidly warming (European) regions—may reach far beyond "just green energy" with regard to sustainability; however, more research is urgently needed.

Removing CO_2 from the air via photosynthesis and pumping it into terrestrial ecosystems is a CO_2 removal (CDR) technique when the total C stocks within an ecosystem increase over time (e.g., soil organic carbon increase, growth of woody biomass), as long as the additionally fixed C remains terrestrial for longer periods of time (decades, centuries). CDR approaches include (i) the use of regenerative or other soil management methods, aimed at increasing the soil organic carbon content [90,91], (ii) the production and (soil) application of biochar produced via pyrolysis from woody grapevine prunings, stems or root wood or dried pomace and (iii), a change towards novel vineyard landscapes where more standing woody biomass elements, in addition to "just" grapevines, accumulate more carbon per hectare over time than grapevine-only landscapes [92,93]. Examples include shifts from vertical shoot positioning to minimal pruning vine row systems which enhance the amount of standing perennial grape wood or planting more hedgerows or tiny forest islands in vineyard landscapes [87] or other vineyard agroforestry systems [92,93]. Lang et al. (2019) [93], for example, demonstrated that the Riesling or Sauvignon Blanc oak or poplar agroforestry (AF) systems improve leaf water potential in order to reach less negative values and increased net N uptake capacity in grapevines, while the chemical composition and sensory quality of the wines were not negatively impacted. One major problem of using "afforestation" or soil-organic-carbon-based methods is that an increased C sink cannot be considered to be permanent. If a vineyard burns down (e.g., in California during the fire season), if agroforestry trees are felled and used in a non-permanent way (e.g., as wood pellets), if the soil is deeply ploughed (increasing SOC mineralization) or if soil-organic-carbon-preserving management is reversed, the fixed carbon can be released again via heterotrophic respiration. Managing and accounting for the exact landscape C stocks at a given point in time to monitor stock increases or decline is methodically a challenge. It is also very labor-intensive when real field/lab measurements are employed [94] instead of models with input–output management balances [95].

The production and application of biochar has considerable potential to reduce the residual CO_2 footprint of viticulture (remaining after all measures for reduction have been taken) by using the vineyard's own materials, but it can also serve various sustainability goals beyond just C sequestration. Biochar (solid), bio-oil (liquid) and permanent pyrogases (and syngases, i.e., CO, H_2 and CH_4) are the products of slow pyrolysis, fast pyrolysis or of gasification. These thermochemical conversion methods convert dry biomasses in the absence of oxygen or at low oxygen concentrations to the three products mentioned above (technology readiness level 8–9). The fraction of each product differs between pyrolysis technologies and feedstocks. While slow pyrolysis optimizes for biochar, gasification is mainly used to produce permanent pyrogases, mostly for thermal energy or electricity generation (e.g., via Stirling engines). When produced at temperatures above 400–450 °C, i.e., with H/C_{org} ratios lower than 0.6, biochars have mean residence times of centuries to millennia when used in soils [96–98]. If biochar is not burned but used as a material (in soils or otherwise), its permanence equates to carbon dioxide removal (CDR) [97,99,100]. The primary "removal" is carried out by photosynthesis while pyrolysis slows down the return to the atmosphere. Pyrolysis with carbon capture and storage (PyCCS, in biochar) has co-benefits for food and fiber production ([101] and metastudies therein); yield improvements have particularly been found in subtropical and tropical soils which could make this form of CDR land-neutral [102]. Adding biochar to organic waste treatment such as composting can reduce gaseous N emissions [103,104]. Using it in soils can reduce N_2O emissions and nitrate leaching [105] and also the uptake of heavy metal cations such as Cu, Zn or Cd into crop plants [106].

In viticulture, reported results on yields are mixed, ranging from "no effect" [107] (Valais, Switzerland, rainfed; [108], Oregon, USA, irrigated) or "positive in some years" [109] (British Columbia, Canada, irrigated) to "beneficial yield effects without decreases in quality" [110,111] (Tuscany, Italy, rainfed). In Tuscany, the research team incorporated either 16.5 or 2 × 16.5 tons of biochar per hectare in 2009 or in 2009 plus in 2010 down to a 30 cm depth in the interrow between vines; they reported that positive effects were still present after 10 years [112]. They found that the yield increases were most pronounced during dry spells that induced drought stress in grapevines (more negative leaf water potential, reduced photosynthetic assimilation at the leaf level), due to biochar increasing the plant-available soil water and thus alleviating yield depressions [111,112]. To date, we are not aware of negative results regarding grape yields or grape must/wine quality characteristics with biochar or biochar–compost use in viticulture, indicating that the worst outcome may be "no effect" (i.e., no economic but environmental benefits). However, more research is clearly needed.

In viticulture, biochar may be amended to soils either untreated (as in Tuscany, Italy [111,112] or in Oregon [108]), as part of organic fertilization (biochar co-composted [107]; biochar and compost mixed [109]) or within organic waste stream management in viticulture (fermented or composted with grape pomace, yeast slurries, etc.), returning vineyard-derived nutrients. Pyrolysis of grapevine prunings, weeded stems, roots or pomace will recycle nearly all of the nutrients, except for nitrogen. About 50% of the original N is lost as N_2 during pyrolysis; most of the remaining N is locked in the heterocyclic rings that compose biochar [113,114]. However, pests and pathogens associated with grape wood would be eliminated at temperatures typically used during pyrolysis (hygienization).

The biogenic pyrogases are mostly burned in modern production plants to generate either heat or electricity or both and can thus replace fossil fuels. Hence, pyrolysis plants are often constructed in places where biomass waste streams or residue are abundant and can easily be collected (e.g., composting facilities) and where thermal heat is needed, e.g., for district heat or greenhouse heating.

Hence, for viticulture regions, cooperatively managed biochar production plants may provide the greatest benefits for wine growers in terms of (a) income supplementation, when the thermal heat or green electricity produced by the pyrolysis unit is monetized, and (b) carbon sink trading revenues [115], i.e., guidelines for C-sink accounting. Voluntary

C-sink trading via biochar commenced in 2020, at higher prices of EUR 100 per ton of CO_2 (compared to normal CO_2 trading), due to the accountability, ability to trace produced charges to their sink destination, the subtraction of processing emissions from the final traded C sink and trustworthiness that result. C-sink trading might be considered by wine estates if their own CO_2 compensation is not intended or CO_2 neutrality is already achieved. Some C-sink traders only reimburse biochar producers, others split the revenues between the producer and the user (here: wine grower), e.g., www.carbonfuture-earth (accessed on 2 April 2023). However, the option to compensate a wine estates' CO_2 emissions with biochar will not free wine estates from reducing their CO_2 footprint, as the following "back of the envelope" calculation demonstrates.

Acquisition of 3 tons of dry pruning wood per hectare and year is assumed. Wood typically has 50% C (=1.5 t ha^{-1}). This would roughly equate to 750 kg of biochar C after pyrolysis (about 50% fixed C) with a modern slow pyrolysis plant. This amounts to 2.7 tons of CO_2 per hectare. Subsequently, we need to subtract at least 0.7 t ha^{-1} for transport and processing in a local facility and reapplication on the wine growers' land, plus we have to consider the (slow) decomposition of biochar in the first 100 years. Therefore, pyrolyzing the pruning wood would result in roughly 1.5 to 2 tons of CO_2 being returned as a biochar C-sink per hectare and year. A wine estate with 20 hectares where all pruning wood is harvested and pyrolyzed may thus allow compensation of up to 40 tons of the wine estate's remaining residual CO_2 emissions. The amount of available biomass of CO_2 compensation via PyCCS may be increased via viticultural agroforestry, hedgerows or other woody biodiversity elements in viticultural landscapes or by (partly) pyrolyzing other winemaking residues such as pomace.

In summary, biochar production from vineyard materials may provide an additional income for wine estates (when a local pyrolysis plant is run cooperatively) and represents a valuable, low-risk soil amendment with potential benefits for global warming adaptation that allows wine estates to compensate residual CO_2 emissions that cannot be avoided.

3.3. Outlook: Greenhouse Gas Emissions and C Sinks

As shown in the previous subsection, the implementation of agri-PV systems in viticulture offers the potential to mitigate substantial amounts of GHG emissions [88]. Assuming an average of 10,700 bottles of wine per ha and a CO_2 footprint of 0.829 kg CO_2-eq. [76], that results in 8.9 t CO_2-eq. per ha and year which is only 1.6% of the CO_2 mitigation system of an agri-PV system. That means 1 ha cultivated under an agri-PV system can mitigate the emissions of around a 63 ha vineyard. However, it has to be kept in mind that the mitigation potential is based on an agri-PV system in which agricultural crops are cultivated [88]. There is a clear research need to analyze the influence of the PV modules on the quality and quantity of the grapes cultivated beneath them as well as a holistic assessment of the environmental impacts of such a system. In addition, the mitigation potential is mainly based on the substitution of fossil energy sources. As the share of renewable energies is increasing, the mitigation potential of agri-PV systems, at least related to the GHG emissions, is decreasing. Therefore, the possibility to remove CO_2 from the atmosphere by using biochar in the vineyard has to play an increasingly large role in the future. As discussed above, the use of biochar has the potential to sequester 2.7 t per ha and year. This corresponds to around 30% of the emissions of the wine production (based on a vineyard of 1 ha). In addition to carbon sequestration the application of biochar may have further positive impacts (e.g., on the yield) [112]. However more long-term research in different climatic conditions and soil types is necessary to assess these effects.

4. Vineyard Inputs

Grape production is one of the phases of the wine life cycle with the highest impact on the environment. The sustainable use of vineyard inputs such as fertilizers, pesticides and water plays a major role in regard to the direct and indirect provision of ecosystem services (ESs), which apart from biomass production encompass pest and disease control, water quality and supply, biodiversity conservation, as well as climate regulation [116]. Thus, the use of the vineyard inputs also has a significant impact on the sustainability of the whole wine value chain. In the following section, the environmental impacts as well as possible reduction strategies of these three central inputs are described and critically discussed.

4.1. Fertilizer

Grapevines do not require large amounts of nitrogen (N), phosphorus (P) or potassium (K) fertilizers when compared to other crops, but fertilization is necessary to ensure productivity in soils with low fertility or deficiency of certain nutrients [64,117]. As the fertilizer uptake efficiency of grapevines is often relatively poor due to a low root length density [117], fertilizer doses historically vastly exceeded plant uptake. Overfertilization has led to a number of severe agronomic and environmental problems in viticulture, among them nutrient imbalances, soil acidification, yield and quality losses by excessive vigor and contamination of freshwater aquifers [118–120].

While integrated production often relies on synthetic N fertilizers, only fertilizers of natural origin such as compost, farm fertilizer and soil conditioners and nutrients are used in organic viticulture [121]. Organic and synthetic fertilizers differ a lot in their environmental impact: pollution related to the production of chemical fertilizers and their field-level emissions are one aspect creating significant environmental burdens in conventional viticulture, while hot spots concerning environmental burdens in organic viticulture involve pesticide use and fuel consumption rather than fertilization [122–124]. However, when using organic fertilization or cover crops including legumes in viticulture there is still a risk of N depletion or enhanced field-level N emissions [116,125].

The contamination risks posed by the respective fertilizer elements are shaped by their mobility in soil: P is highly immobile in soils and K has a relatively low soil mobility, while nitrate (NO_3^-) is highly mobile in soils. Phosphorus thus mainly contaminates freshwater bodies via topsoil erosion events, while NO_3^- is a main contaminant of groundwater due to its high leachability [126]. Roughly 90 % of German vineyards are located in the so-called "red zones" of the European water framework directive with regard to nitrogen, indicating a critical NO_3^- contamination of groundwater resources, and 90 % are also oversupplied with phosphorus (>20 mg P_2O_5/100 g soil).

Precision farming may be an adequate solution to improve fertilizer use efficiency by applying only when and where there is plant demand [127]. Furthermore, foliar application and fertigation have shown better N use efficiencies than granular fertilizer application [128,129]. Controlled uptake long-term ammonium nutrition (CULTAN) fertilization and the application of denitrification inhibitors as well as the side-dressing method have not yet been tested intensively in viticulture, but they offer the potential to increase N fertilization efficiency [130].

4.2. Pesticides

The negative impacts of pesticides on the environment and on human health are widely recognized today, not only in the wine sector, but also in agriculture in general [131,132]. Pesticide use is often associated with contamination of groundwater, degradation of soil fertility, loss of biodiversity and a reduction in ecosystem services such as pest control [133,134]. Thus, the reduction of pesticide use is a key tool to improve viticultural sustainability, especially because viticulture is one of the crops with the highest pesticide use [135,136]. The European Commission announced different pesticide reduction targets within their Farm to Fork Strategy in 2020. The Farm to Fork strategy aims to halve both the amount of pesticides used and the associated risks by 2030 [137].

Quantities of pesticides applied in viticulture and number of treatments can vary highly among different years and locations, depending on the relative importance of each pest and pathogen [57]. Among pesticides used in viticulture in France and Germany, at least 80% are fungicides [138,139]. Downy mildew (*Plasmopara viticola*) and powdery mildew (*Erysiphe necator*) represent the most important grapevine diseases, and together with *Botrytis cinerea* they account for the largest proportion of treatments in vineyards [57]. The first two can cause yield losses of up to 100% when disease pressure is high. In addition, further risks such as a reduction in photosynthetic activity and off-flavors in wines can be associated with them [140–142]. A high number of synthetic fungicides as well as copper and sulfur against powdery and downy mildew are currently authorized and used in viticulture [143–145]. Integrated viticulture mostly relies on synthetic fungicides, which partially act systemically, whereas only the use of copper, sulfur and plant strengtheners is allowed in organic viticulture against powdery and downy mildew [121]. Copper accumulates in the soil and has a high environmental impact on the soil micro- and macrofauna, being potentially toxic to soil organisms and plants in high concentrations [146,147]. Synthetic fungicides, in contrast, can be applied in lower doses compared to copper and do not accumulate in the soil, but often show a high environmental impact due to high energy demand during their production and often unknown secondary effects of their metabolites [122]. Precise quantification of pesticide use in viticulture is not available.

Hill and MacRae (1996) [148] consider efficiency, substitution and redesign as the three main steps in the transition to sustainable agriculture.

1. Efficiency: An increased efficiency of pesticide use is achieved by combining decision support systems, technical improvements as well as agronomic practices. Several mathematical models on powdery and downy mildew development and decision support systems such as VitiMeteo for downy mildew have been developed worldwide, which help growers to adapt their plant protection strategy [57,149]. As a consequence, the number of fungicide applications as well as doses applied could be reduced, leading to an overall reduction of fungicide application [135]. Furthermore, adapted spraying techniques such as recycling sprayers or precision pesticide application allow pesticide reduction and further enhance sustainability [150,151]. In an integrated plant protection strategy, agronomic practices such as defoliation, topping or bunch thinning, adapted soil management and fertilization manipulate vine vigor and leaf area to fruit weight ratio and can thus indirectly contribute to pesticide reduction [152].
2. Substitution: Against powdery mildew, alternatives to synthetic fungicides or sulfur exist. Potassium bicarbonate is successfully used to substitute synthetic fungicides or sulfur partially or entirely, especially in the second half of the growing season. Furthermore, substances such as plant extracts and seaweed, chitin or chitosan mainly act by inducing systemic resistance in the plant, and orange oil as well as antagonists such as *Bacillus amyloliquefaciens* are used to further reduce fungicide inputs [57]. Unlike powdery mildew, few alternative agents to synthetic chemicals or copper against downy mildew have been found [153]. Agents based on potassium phosphonates are successfully used against downy mildew in integrated viticulture [154]. Several substances such as COS-OGA, antagonists such as *Bacillus amyloliquefaciens* and *Saccharomyces cereviciae*, plant extracts or clay minerals can potentially be used at low disease pressure or to reduce amounts of synthetic fungicides/copper [57]. There is still an enormous effort put into finding new solutions to downy mildew infections in viticulture [155]. Insecticide use against grape arthropods is usually nil to moderate in viticulture (0–4 applications per year). Grape berry moths *Lobesia botrana* and *Eupoecilia ambiguella* are of major importance in most wine-growing areas of the world. The biocontrol agent *Bacillus thuringiensis* as well as the mating disruption method based on pheromone dispensers are both successfully used to substitute insecticide applications [57,135].
3. Redesign: Downy and powdery mildew-resistant/tolerant *Vitis* hybrids or varieties combine tolerance against downy/powdery mildew from American *Vitis* species with grape and wine quality of *Vitis vinifera* varieties and are considered as a redesign strategy of the cropping system. These varieties only require a minimal fungicide spraying schedule and allow at least halving the number of sprayings during the growing season [57,156]. Herbicide application is still widely used in the under-vine area to

control weeds. The frequency of application again is highly dependent on pedoclimatic conditions and their use in steep slope vineyards is debated because alternatives are labor-intensive. The use of glyphosate, a widely used systemic herbicide, is being discussed controversially because of its probably carcinogenic properties [157] and several further toxicological effects such as genotoxicity, cytotoxicity, nuclear aberration, DNA damage or chromosomal aberrations and hormonal disruptions [158]. Several strategies exist for redesigning the management of the under-vine area. Tillage and cover cropping are the most common strategies [159] with tillage contributing to CO_2 emissions and cover crops competing for water. Furthermore, covers of straw or bark are successfully used to control weeds in the under-vine area [160].

4.3. Water

Agricultural water use puts a strain on freshwater and wetland habitats and competes with other societal demands for clean freshwater. Water use in grape production comprises the largest water input in the wine supply chain [161], with some authors arguing that water use is a larger constraint for environmental sustainability than pesticide use for most wine-growing regions [162]. Water scarcity has long been identified as one of the most pressing challenges for European viticulture in the context of global warming [12], and the ecological footprint of irrigation in viticulture is expected to rise substantially in its course [35]. Currently, roughly 60% of wine-growing regions are located in semi-arid regions such as the Mediterranean basin, where the economic sustainability of historical dry farming practice is threatened by global warming [163] and shares of irrigated vineyards are steadily increasing [42]. However, even in cool–moderate climate zones such as most regions in Germany, the demand for vineyard irrigation is increasing, especially in vulnerable sites such as steep slopes [33], which provide a number of particular ESs [116].

Irrigation inputs in viticulture vary substantially and have made the improvement of vineyard water use efficiency (WUE) one of the most intensely researched topics in viticulture [162]. Irrigation demand of a vineyard depends on the meteorological conditions of the growing region as well as on the ability of soils to store water, e.g., from winter rainfall. Typical water applications range from 0–160 mm in cool–moderate climates such as Germany [164,165] to 30–300 mm in hot climates with some growing season precipitation [166] and 150–800 mm in hot climates with severe summer droughts, such as the Riverina and Murray River regions of Australia [167,168]. Vineyard WUE depends largely on irrigation technology, strategy, yield target and choice of plant material. Water use efficiency expressed as t of grapes produced per ML water applied may vary from 2–29 t/ML [169], underlining the potential gains that can be achieved by implementing water-saving policies.

Apart from the water consumption and yield provision alone, irrigation can influence a number of other ESs. Soil degradation due to salinization or rising groundwater tables, nutrient leaching and an impact on dry habitat are negative consequences of irrigation, often related to bad irrigation practices [170]. However, there are also positive influences of irrigation on ES provision. Among these are a broadening of possibilities in cover crop establishment and management, with all associated ESs, and increased groundwater replenishment, as well as cultural ESs, provided by the preservation of viticulture in steep slopes and other drought-prone environments.

A number of practices such as choice of adequate rootstocks or soil coverage can increase the productivity and economic viability of dry farmed vineyards [162]. If such measures are no longer sufficient to ensure sustainable yield provision, growers need to resort to irrigation. WUE of irrigated vineyards can be increased in several ways, such as plant material adaptation, deficit irrigation and adequate irrigation technology [42,162]. Historical low-tech irrigation systems such as overhead sprinklers or furrow irrigation have shown a reduction in WUE of about 35% compared to drip irrigation [167], underlining the potential of modern irrigation technology to reduce the water footprint of grape production. Deficit irrigation (DI) strategies are state of the art methods to increase WUE and fruit quality while reducing water inputs. With strategies such as partial rootzone drying, water savings of up to 50% have been reported in the literature [171,172]. The selection of adequate plant material for irrigated viticulture is an important step to increase WUE. Such material could consist of scion varieties with high intrinsic WUE as well as rootstocks adapted to the conditions of the respective irrigation scenario.

Winegrowers can be incentivized to implement water-saving strategies by higher water prices or lower allocations, but also consumer demand for sustainably produced wines and increased spending on water management practice education. To implement water-saving policies, it is further necessary to improve knowledge and data collection on water use on a regional, farm and vineyard scale [173].

4.4. Outlook: Vineyard Inputs

The efficient use of vineyard inputs can increase viticulture sustainability to a large extent, since production and use of fertilizers and pesticides are the main hot spots that create high environmental impacts [78,131]. There is a need to design and adapt cover crop strategies for ensuring grapevine nitrogen supply and simultaneously enhancing biodiversity and preventing nitrate leaching into groundwater bodies under changing climatic conditions. On the other hand, implementation of CULTAN fertilization and denitrification inhibitors can further reduce fertilizer inputs in viticulture.

The use of hybrid grapevine varieties with tolerances against powdery (*Erysiphe necator*) and downy mildew (*Plasmopara viticola*), as outlined in Section 2.2, together with the implementation of new decision support systems, can drastically reduce the number of sprayings from 6–12 to 2–3 sprayings on average per growing season. One very important aspect in this context is the rise of consumer acceptance of these new, hybrid varieties. Future research should also concentrate on plant strengtheners and fungicides of natural origin against downy and powdery mildew and on agronomic measures to reduce disease pressure.

Within the climatic shift, which many wine-growing regions are about to undergo in the near future due to the effects of climate change, agronomic factors such as the adaptation of the soil management and the choice of plant material should be exploited to maintain dry farmed vineyards where possible. Moreover, locally adapted irrigation strategies and technologies are needed to ensure a high efficiency of the irrigation applied. Especially in regions where vineyards are traditionally dry farmed and there is a pressing need to resort to irrigation due to climate change, adapted irrigation strategies are of major relevance.

5. Packaging

From the perspective of environmental sustainability, packaging plays an essential role in the winery sector. Both CO_2 [76,78] and water footprint [174,175] of the wine value chain, as indicators of the use of energy and water resources, and ecological footprint [122,176], as an indicator of material use, identify the packaging materials as a significant environmental aspect in the life cycle of a bottle of wine.

In a future-oriented approach the complete packaging life cycle must be considered, from the extraction of raw materials to packaging production, as well as its use and final disposal. This means that the wine industry has to work together with the upstream and downstream players, in order to develop sustainable solutions and optimization possibilities for the aspect of packaging. In addition to this vertical cooperation, joint approaches should also be sought with other food and, above all, beverage sectors.

5.1. Requirements for Packaging

Packaging can be found in the wine industry as wrapping for viticultural and enological treatment and operating materials, for equipment and for the wine itself. In addition, there is also outer packaging and transport packaging. For example, 565 g of material is used for 0.75 L of wine in the packaging system consisting of the glass bottle, natural cork and six-pack cardboard. A glass bottle of 485 g makes up 86% of this.

In all cases, the packaging has the following functions: (1) it transports the contents from the producer to the consumer, (2) serves for storage, (3) protects against changes or spoilage and (4) conveys product information. In addition, aspects of product and food safety, process engineering, environmental protection, economic efficiency, marketing and legal requirements must be considered. What all packaging has in common is that after the product has been used, it is no longer needed by the user and is therefore considered waste for the time being. In 2020, packaging accounted for 3.69% of the total waste generated in the European Union, which corresponds to 177.2 kg per person [177,178].

5.2. Current Packaging Concepts

The current packaging concepts for wine are diverse. The materials used are glass, plastic, cardboard, metals, cork and wood. In the area of sales packaging, glass, plastics and aluminum are mainly used for the containers and cork, plastics and aluminum for the closures. The largest share is taken by the glass bottle with the various closure options such as natural cork, technical cork, plastic stoppers and the different types of screw caps. Other alternative forms of packaging such as bag-in-box, bottle-in-box, stand-up pouches, cardboard composite packaging and PET bottles currently still have a low prevalence. However, this depends on the country. In Italy, for example, 53% of the wine sold in 2019 was bottled in 0.75 L glass bottles, 28% in carton packaging and 3% in bag-in-box and PET bottles [179]. In France, bag-in-box packaging accounted for 44% of still wine sold in 2021 [180].

The various packaging materials differ considerably in their recovery and especially their recycling rate (see Table 1). Of importance to downstream recycling is that plastics are often used as composites with other materials to improve their properties with respect to product requirements. At present, these composite materials can only be recycled to a limited extent, mostly in a low-grade or energetic use. In the case of outer and transport packaging, cardboard is predominant, sometimes supplemented with a protective plastic film. Wood is mainly used in the form of disposable or reusable pallets.

Table 1. Packaging materials and their recycling [178].

Materials	Recovery Rate		Recycling Rate	
	Germany	EU-27	Germany	EU-27
Paper/cardboard	99.8%	90.7%	84.2%	81.5%
Plastics	99.9%	76.2%	46.2%	37.6%
Container glass	79.7%	76.2%	79.7%	75.9%
Wood	99.8%	61.2%	32.6%	31.9%
Metal	89.4%	77.7%	83.4%	75.7%

5.3. Packaging Concepts for the Future

In terms of future-oriented packaging and material use, the following aspects must be taken into account in the packaging concept for the wine sector [181,182]:

- responsible material sourcing;
- improvement of material efficiency through weight reduction, volume change, design optimization, standardization;
- volumetric efficiency;
- use of more environmentally friendly materials;
- substitution of unsuitable materials;
- use of secondary materials (recyclates from paper, metals, glass or plastics);
- improvement of recycling infrastructure;
- design optimization for reuse or recycling;
- increasing the proportion of reuse and recycling.

In this analysis, the energy use, greenhouse gas emissions, direct and indirect water consumption, material consumption and waste during the production, use and disposal of the packaging must be considered. The inclusion of the entire life cycle of packaging shows that many influencing factors cannot be directly controlled by the wine industry but can only be changed together with the upstream and downstream partners.

The aspect of responsible material sourcing includes the manufacturing process from the extraction of raw materials to the production of the packaging. By selecting a low-emission energy source, the manufacturer of an energy-intensive packaging material such as glass can reduce GHG emissions. Other examples are the consideration of the reusability of the outer and transport packaging and the social commitment of the supplier. Furthermore, due to transport, regionality must be considered in procurement but also in recycling and disposal.

In the case of material efficiency, the material input is considered in relation to the quantity of wine bottled. This includes the lightweight glass bottle, in which less glass is used to contain the same volume. Containing larger volumes also helps to reduce material usage. For example, a 1.0 L glass bottle saves about 10% material compared to a 0.75 L bottle. The bag-in-box systems of 3 L or more or the keg systems of 20 L for gastronomy are further examples. The standardization of packaging materials also leads to improved material utilization. For example, harmonizing or reducing the variety of bottle shapes in combination with glass color can make glass production more efficient, increase reusability and improve glass recycling. The same applies to plastic materials.

The importance of volumetric efficiency can be illustrated by the transport volume of empty material. To contain 100,224 L of wine, 133,662 0.75 L bottles are required. This is equivalent to 96 industrial pallets per 1392 bottles. This will take 3.7 trips of a 40-ton truck. If the wine is contained in 1.5 L stand-up pouches, 66,816 pouches are needed, which are delivered on 12 industrial pallets with 5600 pouches per pallet; this corresponds theoretically to 0.5 trips of a 40-ton truck. Another example is the bulk transport of imported wines and filling sales packaging in the region of consumption.

Use of more environmentally friendly materials involves giving preference to bio-based, renewable but also lower-emission raw materials in the manufacturing process. For example, if paper fibers are replaced with grass fibers in a cardboard wine container, water and electricity can be saved. For stability reasons, this is possible up to a maximum of 40% [183]. Another example is the use of sugar cane to produce bioplastic, which is then used, for example, to make plastic stoppers. However, it should be noted here that this polyethylene plastic made from renewable raw materials, like its counterpart made from crude oil, is not biodegradable and should therefore be fed into an organized recycling process. Furthermore, the use of plant-based raw materials for packaging production competes with food production. Bio-based plastics also have a higher acidification potential than plastics made from fossil raw materials [184].

In this context, unsuitable materials have to be replaced by more suitable ones. One major point, especially in the context of reducing the environmental impact, especially GHG emissions, is the replacement of the glass bottle. Reasons are the energy-intensive production, in connection with its weight and the transport emissions, in comparison to alternative packaging forms. Bag-in-box packaging, other pouch packaging, composite cartons, PET bottles and cans have a lower weight and carbon footprint by approximately 66–90% compared to the standard one-way glass bottle [76,185,186]. The CO_2 footprint for different packaging types in kg CO_2-eq per 0.75 L wine is shown in Table 2. In terms of recyclability, Table 1 shows similar recycling options for the alternative materials. In the case of plastic materials, recycling needs to be improved. Additionally, depending on the type of wine, the product quality does not reveal significant differences for consumer wines with a lifespan up to 15–24 months [187,188]. At the same time, less oxidation-sensitive products, such as red and rose wines, can be bottled in the plastic materials, which are not completely gas-tight as an example from France demonstrates [180].

Table 2. CO_2 footprint for different packaging types [83].

Packaging Type	kg CO_2-eq per 0.75 L
Average Bottle, EU	0.472
Light Bottle, EU	0.387
Heavy Bottle, EU	0.728
Bag-in-Box 3 L	0.052
Beverage Carton 1 L	0.063
PET 0.75 L	0.182
Pouch 1.5 L	0.071

The use of secondary materials is in line with the closed-loop concept. Thus, not only is raw material directly saved by reuse but also other resources such as energy and water. This applies to most packaging materials in the wine sector, such as paper, glass, metals and plastics. For example, in glass recycling, it is assumed that 3% of energy can be saved for every 10% of glass cullet used [189,190]. Another example is the use of secondary aluminum, which requires only 10–15% of the energy in the production process. This corresponds to GHG emissions of 1.9 t CO_2 eq. t^{-1} compared to 11.9 t CO_2 eq. t^{-1} for primary aluminum [191].

The optimization of the closed-loop use of materials must also be coupled with an improved recycling infrastructure in conjunction with an adaptation of the packaging design. This is clearly illustrated by the example of plastics. Here, the difference between recovery and recycling rates shows that a large proportion of plastic materials are collected but are not sufficiently sorted to be reused (see Table 1). In addition to a reduction in the variety of plastics and more targeted sorting, new approaches have to be developed which make it possible to separate composite plastics or replace them with recyclable materials. This applies to the PET bottle and bag systems such as bag-in-box or stand-up pouches.

In addition to the material cycle, the reuse of packaging is also an option, especially for energy-intensive forms of packaging such as glass bottles. In this case, it is necessary to discuss the glass recycling cycle with the reusable cycle in connection with the individual transport routes. In this discussion, it quickly becomes clear that the entire value chain of the packaging sector, the wine industry, the wine and food trade and the customers must pull together and create framework conditions for the multiple use of wine bottles. These are, among others, the reduction of bottle diversity, the possible introduction of a pool bottle and deposit system with bundled return and this in cooperation with other beverage sectors such as beer or mineral water, regional distribution in conjunction with the establishment of a regional rinsing center network, the removing behavior of the labels, the higher risk of breakage during filling with possible consequences for consumer protection, the changed visual appearance of the bottles after a few cycles and much more. In this context, the reusability of the outer carton must also be considered.

5.4. Outlook: Packaging

All the environmentally beneficial aspects of material use, weighed against the other subaspects of product quality, food safety, process engineering, logistics, marketing, economy and society, ultimately lead to the selection and development of individual, in-house and possibly also regional packaging concepts, or to the parallel use of different concepts. Many wineries already offer various packaging alternatives in parallel, depending on the product characteristics, the target group, the target market and the customer's wishes: lightweight glass bottles, disposable bottles, reusable bottles, PET bottles, stand-up pouches, PE pouches in cartons, bags-in-boxes, composite cartons, cans and large-volume container systems, either for self-filling or for filling by others.

All concepts have their justification in a holistic sustainability view, taking into account the respective perspective, but with regard to the planetary boundaries according to

Steffen et al. (2015) [3], a future-oriented packaging concept must go further than company-specific solutions. The wine industry must take a common path in order to effectively reduce the environmentally relevant aspects—led by the reduction of GHG emissions. This includes the rationalization of the packaging system, in which glass consumption is the most significant factor. Standardization, improvement and regionalization of material cycles using alternative packaging are solutions that must be tackled jointly along the entire wine value chain, or even better, the entire food sector. This is especially true in view of the fact that a large part of wine and food is sold through food retailers and supermarkets, which have to accept and implement novel sustainable packaging concepts as well as communicate them to their customers [192,193].

6. Social and Economic Challenges

In the following section major economic and social challenges in the transition to a holistic sustainable wine industry are discussed. In the first subsection a focus is placed on the economic challenges and possible solutions and emerging opportunities are shown. One major hurdle in the successful sustainability transformation is the shortage of highly trained employees who can help shape this process. Therefore, the availability of labor and human resources is discussed and the role of education to develop a sustainable wine industry is highlighted.

6.1. Economic Sustainability in the Wine Industry

The concept of economics can be traced back to the Greek language as "study of managing scarce resources" [194]. From a sustainability perspective, there are several definitions of economic sustainability. Differences between the definitions are the result of different sustainability models as a starting point. On the one hand, economic sustainability is understood to be economic development that does not have a negative impact on ecological or social sustainability. Hence, an increase in economic capital must therefore not be at the expense of a reduction in natural capital or social capital. On the other hand, economic sustainability is equal to economic growth. Economic growth is considered sustainable as long as the total amount of capital increases. However, increased economic capital can be allowed at the expense of a reduction of other assets in the form of natural resources, ecosystem services or welfare [195].

A more practical approach to appraise economic sustainability is to evaluate economic feasibility and performance by employing economic assessment studies. There are three main methods that have been used in a wide range of economic assessment studies for the purposes of: (1) monitoring the performance of the existing system related to economic sustainability and (2) comparing several alternative options and identifying the most cost-effective option among them to attain particular objectives. These are cost-effectiveness analysis (CEA), cost–benefit analysis (CBA) and multicriteria analysis (MCA). The complex and multifunctional nature of renewable sources-based systems may require economic sustainability assessment methods that comprise multiple and variable criteria representing a range of costs and benefits derived from alternative options. In addition, these criteria may not be quantified and expressed as monetary values, instead, they can be defined in terms of qualitative statements and other units [196].

Besides the problem of measuring and interpreting qualitative statements precisely and objectively, another problem might lie in the fact that the mainstream of the literature on corporate sustainability follows the win–win paradigm, according to which economic, environmental and social sustainability aspects can be achieved simultaneously; indeed, corporate sustainability has often been defined by the intersection of these three areas [197]. However, given the multifaceted and complex nature of sustainable development, Hahn et al. (2010) [198] argue that trade-offs and conflicts in corporate sustainability are the rule rather than the exception. Turning a blind eye to trade-offs thus results in a limited perspective on corporate contributions to sustainable development [199].

In the light of trade-offs an alarming development in the wine business has to be discussed. On 16 February 2022, a guiding decision was made when the European Parliament voted on "Strengthening Europe in the fight against cancer". The text was adopted by a large majority in Parliament (652 votes in favor, 15 against and 27 abstentions) and contains numerous recommendations for action to develop an EU-wide strategy to combat cancer. In addition to the consequences of general nutrition (such as obesity), the proposed interventions include the effects of various types of radiation (e.g., UV radiation) and environmental pollution, as well as the consumption of tobacco and alcoholic beverages as important risk factors for cancer. The following recommendations for action were introduced for the alcohol sector: (a) provide improved information to consumers, (b) restrict alcohol advertising and sponsorship activities and (c) revise pricing, including consideration of increasing taxes on alcoholic beverages [200]. In the context of this development there is a strong increase in the interest in no- and low-alcohol wines. These wines might bear potential for market growth and might have positive effects on social welfare and health care systems. However, the ecological effects of reducing alcohol have not yet been discussed.

A recent study of the consulting company Deloitte has shown that climate change remains high on the agenda of executives. At the same time, there is still a gap in many organizations between an understanding of the urgency of the issue and the concrete embedding of sustainability in strategy, operations and corporate culture [201]. According to the top managers, economic growth can be achieved in line with climate goals. Much more speed is needed though in implementing climate protection measures and in adapting to climate change. However, if every company views sustainability as a means to achieve a competitive advantage the questions arises whether advantages turn out to be points of parity in reality.

In the context of Sustainable Development Goal No. 9 (to build resilient infrastructure, promote sustainable industrialization and foster innovation) the International Organisation of Vine and Wine (OIV) presented in its study "Digital Trends in the Vine & Wine Sector" that blockchain technology has the greatest potential of all digital technologies in the wine industry [202]. However, in the context of sustainability blockchain technology has to be seen as a two-edged sword. On the one hand it might result in very effective economic advantages, whereas, on the other hand, high energy needs contradict ecological sustainability [203].

6.2. Labor and Human Resources

Despite an ongoing process of mechanization and automation at the upstream grower level, manual work, "labor" or "human resources" still play a key role in all wine-producing countries—to a greater or lesser extent. In this regard sustainability depends on four challenges: labor market supply, skills, wage costs and productivity. The latter is intimately linked to the quality of the relationship between employer and employee.

South Africa serves as a case study to illustrate these universal challenges. Here, in the past mass production mostly went hand in hand with adequate labor supply, a basic skills regime, low costs and authoritarian labor relations. To be sure, this era was not without periodic crises, but in the 20th century a minimum pricing structure and access to political power provided a reasonably stable existence for most growers. They were rewarded on volume rather than quality. In exchange the growers supported successive white governments [204]. Workers were living on the margins, but in a situation of high unemployment and no labor or political rights, there was little they could do. Until late into the 20th century wage costs were so low that the inefficient use of labor hardly mattered [205]. This changed markedly with the onset of the "quality" era in the early 1990s. When the growers realized that they were about to lose their access to political power, they began to transform their modus operandi. They replanted their vineyards, employed new vineyard practices and modernized their cellar operations. At the same time the industry was deregulated step by step. For a while it appeared as if they had made a seamless transition. Exports were doing well, fueled by international interest in South Africa, as well as a weak currency. However, that benefit soon evaporated. By the mid-2000s exports started to stagnate and decline while domestic inflation eroded whatever benefit successive currency devaluations conferred [206]. Financial pressures increased further when labor rights were extended to farm workers (incl. a minimum wage) and overseas clients started to demand compliance with environmental and food safety codes towards the end of the 1990s [207]. Growers responded by downsizing the core, on-farm labor force and sourcing external contract labor on a bigger scale. The former had to be taught new skills, especially with regard to trellising systems, pruning and canopy management. This "externalization" reduced labor costs but caused new concerns about the skills of contract labor. The skills issue gathered additional urgency when "climate change" entered the industry agenda in the 2010s. Increasing minimum and maximum temperatures in the Cape winelands could no longer be ignored [208]. Growers who were in a financial position to plant new varieties or acquire vineyards closer to the coast did so. Others started to experiment with different vineyard practices and trained their workers accordingly [209]. However, all this means higher costs and it is mostly those who have established their own brands and can set their price that are in a position to do so. Most South African growers find it difficult. Continually rising labor and input costs are one part of the financial squeeze. The other is the thin margins offered by clients. Although the average quality of South African wine has improved continuously since the mid-1990s, almost two-thirds is exported in bulk. At this quality level the returns are modest [207].

The dire situation experienced by the majority of producers was further aggravated by the COVID-19 pandemic. In 2020 the government issued a five-week export ban and an even longer domestic alcohol ban. The losses in revenue ran into billions [210]. The upshot of these developments is a big shakeout of growers over the last thirty years. Their numbers have been reduced from roughly 4600 in the mid-1990s to approximately 2600 in 2022 and he industry may not have seen the end of it. In January 2023 the CEO of an organization that is in close contact with growers (i.e., Vinpro), told a public forum that only 9% of South African growers made a "sustainable profit" [211]. If these figures are correct, there is little doubt that for at least a third of the growers the return on investment is so low that grape production is not sustainable in the medium to long term. This also means that they have little if any capital to invest in practices that can mitigate climate change (e.g., planting new varieties) or absorb the higher wage costs implied by more intensive labor practices. It is not the supply or the skills that are the problem, but the higher wage costs involved in more labor-intensive, climate-oriented vineyard practices. As a means of survival those growers, whose profitability is threatened, are likely to stick to the low-quality, high-yield business model, i.e., continue on the commodity path. Even so, a considerable number are bound to exit the industry over the next five to ten years. Thus, in its current form the South African wine industry does not appear to be sustainable. It will be up to the survivors to do the "right thing". In other words, to make the move away from bulk wines towards the industry's declared goal of "premiumization" and branding—whilst keeping an eye on the changing climate in the vineyard.

Although South Africa may illustrate the general labor challenges facing growers all over the world, it could be regarded as an extreme case. There may be no other wine-producing country where growers have to face a purely market-driven environment and a non-supportive state to the same extent. Here labor will be less of a challenge in the overall pursuit of sustainability.

6.3. The Role of Education to Develop a Sustainable Wine Industry

None of the aforementioned challenges can be addressed without rethinking education and the role of educational institutions. From future industry leaders and decision makers to researchers, educators, administrative staff and wine growers on the ground, everyone will have to be equipped to deal with the changes that come with developing a sustainable wine industry. Education is the key in the development of a sustainable future [212]. In 2002 the United Nations World Summit on Sustainable Development adopted an action plan calling for a decade of education for sustainable development (DESD), starting in 2005 [213]. The final monitoring report on the DESD emphasized a greater visibility of education for sustainable development (ESD) and that it is of utmost importance that sustainability will become mainstreamed in all educational programs and environments irrespective of the level/type of teaching institution [214]. Without a serious step to deep-root these issues in academic and non-academic learning environments, the personal and societal transformation that is necessary to change the course of any industry will not be successful. In 2020 the roadmap to implement UNESCO's Education for Sustainable Development: Towards Achieving the SDGs (ESD for 2030) framework reiterated the need for "transforming learning environments" through an alignment of learning institutions with sustainable development principles, stating that the "whole-institution approach to ESD calls for learning environments where learners learn what they live and live what they learn" [215]. Whole institution approaches "encompass mainstreaming sustainability into all aspects of the learning environment" [214]. That means that sustainability is established as a core objective of the organizational development of educational institutions, from campus management and operations to curriculum design and community partnerships. More emphasis needs to be placed on implementing such approaches in order to address the urgent sustainability challenges and promote the necessary individual and societal transformation going forward.

6.4. Outlook: Social and Economic Challenges

Improvements in environmental and social sustainability often lead to higher or additional costs and can thus decrease the economic sustainability. In order to understand possible trade-offs between the three dimensions it is therefore crucial to analyze the economic as well as environmental and social impacts when assessing the sustainability of novel approaches along the whole wine value chain.

In addition, it can be seen in this section that the availability of well-educated workers is central for the transition to a sustainable wine industry. Therefore, educational institutions have not only to ensure the necessary quantity of graduates but also that they have the necessary skills to successfully steer this transformation process.

7. Conclusions

Wine is often perceived by many consumers as a natural and sustainable product. However, there are several environmental and socio-economic challenges which the wine industry has to overcome in order to do justice to this assessment. The ongoing global warming with its negative effects on cultivation emphasize the need for a rapid transformation towards more sustainability. Breeding new resilient varieties is essential in order to adapt to the changing environmental conditions. These new varieties could also help in reducing the application of input substrates and thus also the associated negative environmental impacts. However, adaptation to climate change is only one part. The wine industry must also live up to its responsibility and reduce its GHG emissions. Besides changes in the packaging system (e.g., from single use to multiple use) and the reduction of input substrates, the implementation of agri-PV systems in vineyards as well as the application of biochar to sequester carbon in the soil can play an especially major role in mitigating GHG emissions. The integrated use of these approaches could enable a resource-conserving, biodiversity-promoting and carbon-neutral wine production with multiple benefits for society. However, in order to further develop these approaches and implement them in practice, well-educated viniculturists, winemakers and researchers are crucial. Here, the educational institutions, such as universities, are obliged to implement all aspects of sustainability in the teaching programs and overall learning to raise the awareness and know-how on these issues for the next generations.

However, various approaches to improve the sustainability of the wine value chain also lead to an increase in production costs. This might represent an insurmountable barrier for the implementation of sustainable practices in the current time of increasing socio-economic pressure on the wine industry. An increase in the environmental and social performance can therefore not be achieved without the inclusion of the economic dimension. If we as a society want a more sustainable wine value chain and to retain winegrowers as managers of cultural landscapes as well as providers of various positive ecosystem services we must also be willing to pay more for these products.

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