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RESEARCH ARTICLE

Emerging Sustainable Practices in Cool Climate Viticulture: A Case Study from Sweden

Karl-Johan Fabó[1]*, Lotta Nordmark[2], Anna Ternell[3], Sándor Némethy[1,4]

[1]*University of Tokaj, Mathiasz Institute, Sárospatak, Hungary*
[2]*Swedish University of Agricultural Sciences, Department of Biosystems and Technology, Alnarp, Sweden*
[3]*RISE Research Institute of Sweden*
[4]*University of Debrecen, Kálmán Kerpely Doctoral School, Debrecen, Hungary*
**Corresponding author's email: karl-johan.fabo@unithe.hu / kj_fabo@hotmail.com*

Abstract – The Swedish wine culture is comparably young, and its domestic wine production is even younger, starting with the official approval by the European Union in 1999. While domestic wine production currently contributes modestly to the Swedish economy, the industry is experiencing notable growth. It attracts investments, gains national and international media attention, and demonstrates a strong determination to thrive. Swedish winemakers have by now shown the ability to produce highly appreciated and award-winning wines from locally grown grapes. Furthermore, recent studies conducted within the context of ongoing global warming indicate the possibility of a future, more extensive wine industry in cold climate regions, such as southern Scandinavia.

In this study, we evaluate the great potential of recent emerging Swedish wine regions, which demonstrate the crucial role of research in achieving industry success. Some pioneering Sweden-oriented viticulture and oenology research has been conducted, some of which is shown in this paper, indicating a possibility to diversify the used grapevine cultivars in the Swedish production. Overall, more research will be needed to advance wine farming in still relatively unknown territories. Given Sweden's robust sustainability goals and the absence of rigid regional wine regulations, there is both a need and an opportunity for the development of locally adapted, sustainability-driven wine production methods. In this context, unique opportunities exist for practitioners and researchers to explore highly sustainable approaches, such as regenerative viticulture and multifunctional agriculture. These approaches have proven successful in other parts of the world, despite their current limited broader application.

Keywords – organic viticulture, cover crops, regenerative viticulture, cold climate viticulture, sustainability, PIWI, resistant varieties, climate change, multifunctional agriculture, newclim

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1. INTRODUCTION

Cool climate viticulture is gaining increasing attention in regions with a mean growing season temperature less than 16 °C, where growers face the need for cold-hardy cultivars (Jones & Schultz, 2016). Such cultivars need to be able to withstand low temperatures and extreme weather, diseases, and ripen in short growing seasons, while also being productive. Due to the expansion of grape growing areas in cold climate regions, the need for reliable grapevine cultivars increases continuously, particularly in view of a warming climate, which changes the ecological conditions, grapevine distribution, and phenology, and the boundaries of traditional winegrowing regions (Gutiérrez-Gamboa & Mucalo, 2025). The most important steps to create an environmentally, phenologically, and economically sustainable vineyard in new climate zones are:

- The choice of the terroir – geomorphology (aspect), soil, water, climate, and microclimate.
- Identify grape cultivars that are or can be adapted to the chosen area.
- Assess the cultural requirements of grape cultivars grown under the local climatic conditions.
- Evaluate the winemaking and quality potential of grape cultivars under different climate and soil conditions within the region.

Grapevine breeding programmes targeting cold hardiness, climate resilience, disease resistance and better productivity have been run both in Europe and in the New World. In Germany (Geisenheim, Freiburg, Geilweilerhof) and in Austria (Klosterneuburg), research programmes have been conducted continuously since the 1920s. These sustained efforts have resulted in a wide range of resistant grape cultivars, such as the widely available PIWI (PIWI = Pilzwiderstandsfähigen Rebsorten, e.g. Voltis, Vidoc, Hibernal, Orion, Phoenix, Regent, etc.), which have brought significant international recognition (Töpfer et al., 2022, Németh, 2024). In Hungary, grape breeding can be traced back to private breeders in the late 19th century, leading to pioneering work in both intra- and interspecific crossings (Hajdu, 2015; Fazekas et al., 2022). This development transitioned into governmental institutional programs in the early 1950s, where breeding targets included traits such as disease resistance, early maturation, and cold hardiness. To name a few, this has resulted in white fungal-resistant PIWI-varieties such as Bianca and Zalagyöngye, and the red variety Néró, bred by Dr. Csizmazia (1918-2013) and his team at the Research Institute for Viticulture and Enology in Eger. Notably, today the fungal-resistant and early maturing Bianca is the most widely grown white grape cultivar in the country, used mainly for bulk- and table wines (Fazekas et al., 2022).

In the United States, extensive breeding research has produced numerous resistant and cold-hardy varieties. Many of them were the result of the pioneering work of Elmer Swenson, the world-famous viticulturist of Swedish descent from the Upper Midwest region of the US (Clark, 2019). St. Croix, La Crosse, Edelweiss, and Swenson Red are a few examples of cultivars resulting from his breeding work. In the US, cold-hardy varieties are often French-American hybrids, created by crossing Vitis vinifera (hardy only to -21°C) with American native grapes such as Vitis riparia, V. rupestris (Sand grape), V. aestivalis (Summer grape), and V. riparia (Riverbank grape). This research at centres mainly including Montana State University, Cornell University, the University of Minnesota, and North Dakota State University has produced thousands of new cultivars of cold-hardy and fungal-resistant wine and table grapes.

Figure 1. Clarion – a new cold hardy Grape variety from University of Minnesota. *Source: Clark et al. 2023.*

Clarion (Fig. 1), VB86-4 (Seyval blanc × Pinot Noir) × Frontenac (Riparia 89 × Landot 4511), developed at the University of Minnesota and released in 2022, is an interesting example of a cold-hardy white grape cultivar that produces excellent, high-quality, aromatic, dry white wines (Clark et al., 2023).

Wine has been imported to Sweden at least since the country's Christianization in the 11th century (The Museum of Spirits n.d.). The draymen, who were licensed to transport and distribute imported wine in the city of Stockholm, represented Sweden's last active guild, dissolved in 1930 (The Museum of Spirits n.d.; Fig. 2).

Figure 2. The symbol of the draymen's guild (a pipette and a knife) on a 17th-century building in Old Town, Stockholm. *Photo: K-J Fabó.*

However, traditionally, Sweden has been part of the "vodka belt"—a northern region characterised by high production and consumption of distilled spirits (Rauhut Kompaniets, 2022). The fermented grape beverage remained for a long time largely an exclusive product for the church, royalty and elite (The Museum of Spirits, n.d.). Several factors in the second half of the 20th century contributed to shifting alcohol preferences and drinking habits in Sweden, with wine eventually becoming a major contributor to total alcohol consumption. These factors include a growing middle class traveling to southern Europe for vacations, labour immigration from traditional wine countries such as Italy and Greece, as well as governmental campaigns aimed at reducing heavy liquor consumption (The Museum of Spirits, n.d.; Centrum för Näringslivshistoria, n.d.).

In the recent three decades, the Swedish wine culture has evolved even further, with an emerging domestic wine industry that now can supply customers with locally produced wines. When the country gained EU recognition as a wine-producing nation in 1999, Swedish wine farming pioneers could transition their hobby productions into commercial ventures (Fig. 3) (Nordmark et al., 2016). The EU recognition placed Sweden within the winegrowing region Zone A, along with most of Germany (excluding Baden), Luxembourg, Belgium, Denmark, Ireland, the Netherlands, Poland, the United Kingdom, and the Czech

region of Čechy (Council Regulation (EC) No 1493/1999, 1999).

Figure 3. Vine rows at Vingården i Klagshamn, a pioneering vineyard in Sweden. *Photo: K-J Fabó.*

Since Swedish commercial wine farming is a very young endeavour, the scientific literature on the topic is still limited. However, some previous studies regarding Swedish wine farming have highlighted aspects such as the general potential for a domestic industry (Gustafsson & Mårtensson, 2005), economy (Mårtensson et al., 2013, Larsson & Nordmark, 2022), oenoleptic qualities of Swedish wine (Nordmark et al., 2016), environmental aspects (Mårtensson, 2020), and wine tourism and marketing (Rauhut Kompaniets & Nilsson, 2023; Rauhut Kompaniets, 2022). Collectively, previous studies indicate the potential of Swedish wine farming, although with obstacles to overcome. In recent years, Swedish wine farming has experienced a rapid increase, marked by a shift in public opinion from initial doubt to growing acceptance and appreciation. Simultaneously, there are global calls for transitioning to sustainable agricultural practices and climate resilience. Therefore, this study aims to: (1) provide an updated general overview of the current state of Swedish wine farming; (2) investigate the potential for introducing new grape varieties to broaden the list of fungal-resistant varieties that can meet consumers' demands for new wine styles; and (3) explore the potential for researching and implementing sustainable cultivation methods through holistic and sustainable approaches.

2. Materials And Methods

This paper adopts an intrinsic case study approach, primarily aiming to describe the case with an inherent interest in the topic itself, rather than to generate results for generalisation or theory building (Johansson, 2003). It is motivated by the specific and unique phenomenon of emerging Swedish wine farming and its relation to sustainability regarding factors such as climate, national regulations, and market preferences. To capture the case's complexity from multiple angles, a mixed-methods approach is employed, which combines qualitative and quantitative methods. This includes a narrative literature review (Bryman, 2018), unstructured interviews with Swedish wine farmers conducted during vineyard visits and field observations, and a climatic study calculating growing degree-days (GDD) for southern Sweden. Moreover, results from a vineyard pilot trial with less common grape varieties in southern Sweden are included.

The narrative literature review was conducted to contextualise the emerging phenomenon of Swedish wine farming and its relation to sustainability, and to identify gaps and potential areas for further research. It aimed to: (1) explore the historic background to the emergence of Swedish wine culture and wine farming; (2) identify existing research on the Swedish wine industry; (3) investigate the current state and future viability of wine farming in the country; (4) identify critical global sustainability challenges in wine farming and their relevance to the Swedish context; and (5) identify holistic sustainability concepts applicable to or warranting further research within Swedish wine production. The literature search primarily utilised academic databases (Google Scholar and Web of Science), as well as Google to acquire industry reports from agricultural and wine organisations, relevant government and EU publications, and news articles. Sales statistics regarding Swedish wine were obtained from Systembolaget (the national alcohol retail monopoly) upon their provision. Historic information on wine consumption in Sweden was attained from the webpages of The Museum of Spirits in Stockholm and Systembolaget.

Audio-recorded interview data, originally collected by the corresponding author for two previous magazine reports (Fabó, 2024; Fabó & Németh, 2023), were re-analysed for this study to gain in-depth and nuanced perspectives on emerging Swedish wine farming and its relation to sustainability practices. Conducted in an unstructured manner (Bryman, 2018), these interviews allowed participants to freely share their experiences, perspectives, and insights without the constraints of pre-determined questions or response options, aligning with the exploratory nature of this study. A general topic guide, focusing on motivations for wine farming, views on the future of Swedish wine production, and an approach to sustainability, initiated the conversation. The interviews were largely open-ended, allowing participants to elaborate on aspects they deemed most relevant. Five vineyards, each represented by their responsible vineyard manager(s), were included to ensure diversity regarding factors such as level of experience (pioneer or more recently established), education in viticulture (self-taught or schooled in viticulture and oenology), origin (from Sweden or a traditional wine country), gender, and vineyard size. Interviews typically lasted between 45 minutes and 1 hour and were subsequently transcribed to facilitate detailed analysis. These interview transcripts were combined with field observations at each vineyard, allowing for the observation of factors such as ground cover use. The participants were informed and consented to the re-utilisation of the recordings for this study. The collected and

analysed interview data, along with notes from the field visits, contributed to the holistic understanding of this case.

The methodologies for the two earlier unpublished studies conducted through the Swedish University of Agricultural Sciences (Nordmark, L.)—specifically (1) measurements of growing degree-days (GDD) for southern Sweden and (2) a grape variety pilot trial in southern Sweden—are described below.

Growing degree-days (GDD) for southern Sweden

Growing degree days (GDD), using a base temperature of 10°C, were calculated and documented for a seven-year period (2018-2024) in southern Sweden by Adcon weather station (OTT HydroMet GmbH) 150 cm above ground to examine the development and possibility of grapevine cultivation. The calculations covered the period from April 1st to October 30th, following the method of Winkler et al. (1974).

$$\mathrm{GDD} = \sum_{i=1}^{n} (T_i - T_b)$$

Grape variety trial, southern Sweden

In a project between Kullaberg's Vineyard (Kullabergs Vingård), Partnership Alnarp (Partnerskap Alnarp), and the Swedish University of Agricultural Sciences (SLU), a pilot trial with several red and white fungus-resistant PIWI varieties was established in 2017 (Table 1).

The grape variety pilot trial was evaluated for sugar content at harvest (°Bx) and harvest yield (kg per plant) over three years (2021–2023). The grapes were harvested at the same time each season, in the first half of October (specifically on October 13, 2021, October 11, 2022, and October 16, 2023), which is the beginning of the harvest period in the region. The trial was set up with 20 plants per variety, all grafted on rootstock SO4. In addition, the Cabaret Noir variety was also grafted onto the rootstock AA125. All measurements were conducted at harvest, before the grapes were prepared for micro-fermentation.

All values are presented as mean ± SE. Data were statistically evaluated using analysis of variance (GLM). All statistical analyses were performed using the statistical software MINITAB (Minitab Inc., USA). A significance level of $p<0.05$ was used unless otherwise indicated.

Table 1. List of the red and white PIWI varieties included in the trial with variety name, pedigree, plant breeder, country, year of crossing, and year of protection. *Source: Röckel et al., 2025*

Varieties	Pedigree as given by breeder/bibliography	Breeder	Country	Year of crossing	Year of protection
Red Varieties					
Roesler	Zweigelt x Klosterneuburg 1189-9-77 (Seyve-Villard 18-402 x Blaufraenkisch)	Gertrude Mayer	Austria	1970	1999
Pinotin	Pinot Noir x *	Valentin Blattner	Germany	1991	2007
Cabernet Jura	Cabernet Sauvignon x *	Valentin Blattner	Switzerland	1992	*
Cabaret Noir	Cabernet Sauvignon x *	Valentin Blattner	Switzerland	1991	*
CAL 1-28	Vitis Interspecific Crossing	Valentin Blattner	Switzerland	*	*
Pinot Nova	Blauer Burgunder x Malverina	Ferdinand Regner	Austria	1990	*
White Varieties					
Donauveltliner	Gruener Veltliner x Seyval Blanc	Ferdinand Regner	Austria	1996	*
Cabernet Blanc	Cabernet Sauvignon x *	Valentin Blattner	Germany	1991	2008

Riesel	Riesling x *	Valentin Blattner	Switzerland	1989	*
Sauvignac	(Sauvignon x Riesling) x *	Valentin Blattner	Switzerland	1991	2018

*Unpublished or unregistered

3. Results and Discussion

3.1 The expansion of Swedish wine farming

Although Sweden's contribution to global wine production is still modest, the industry is experiencing steady growth (Persson, 2024). While there were only three registered commercial winegrowers in 2005, the number reached 57 in 2023 (Hansson, 2006; Persson, 2024). New vineyards are being established across the country, and wine cellars with expanded production capacity are being built to meet increased yields (Sarnholm, 2022; Rader, 2024; Bryant, 2022). In 2022, the sports car manufacturer Koenigsegg made the single most significant investment in Swedish wine, by planting 85,000 vines on 20 hectares in Southern Sweden (Hallvarsson & Halvarsson n.d.; Fig. 4). Official data from the Swedish Board of Agriculture (SJV) shows an 89% increase in the total grape vine acreage in the country between 2017 and 2020 (from 56 ha to 106 ha) and a 51% increase between 2020 and 2023 (to a total of 160 hectares) (Persson, 2024). In 2023, the total grape harvest of 304 metric tons was almost double that of 2020, which was 155 metric tons.

Figure 4. The photo depicts vineyard development seen in the region, such as the 2022 investment by Koenigsegg, 85,000 vines planted on 20 hectares (Hallvarsson & Halvarsson n.d.). *Photo: K-J Fabó*

During the few decades of commercial wine production in Sweden, there has been a rapid improvement in the wine quality. By now, Swedish wines demonstrate a high international standard, as evidenced by awards in recognised competitions across Europe (Livets Goda, 2021). In 2024, a comprehensive international blind tasting - the "Swedish Wine Tasting 2024" (TSWT) - was held in Ängelholm, Sweden. Four of the eight top wines were Swedish, including the top-ranked wine from the 18-hectare Kullabergs Vingård (Kullaberg's vineyard) in Skåne, the southernmost county (TSWT, 2024). Today, Swedish wines are being exported to approximately 10 countries, even if still in small quantities (PIWI International, 2024).

3.2 Domestic market characteristics

In Sweden, white still wines are the main category regarding production (Systembolaget, n.d.). Although sparkling white wines are an increasing category, and still and sparkling rosé wines, and to some extent red and orange wines are also produced. Due to the cold climate, sparkling wines are recognised as a particularly suitable wine style for the country (Stigh et al., 2016; Fabó, 2024). The cold climate naturally results in high acidity in the must, a crucial quality criterion for sparkling wines. Moreover, consumer trends for this type of wine are still on the rise (Global Market Insights, 2025). Extensive experimentation is ongoing regarding different barrel aging methods, where barrels are utilised not only from established wine countries (such as France, Germany, USA, and Hungary) but also from Swedish oak (Systembolaget, n.d.).

In Sweden, the only retailer for beverages with an alcohol content exceeding 3.5% is the government-owned chain Systembolaget. In addition to Systembolaget, Swedish wine farmers sell their wines directly to restaurants and to a small extent also export. Some vineyards have their own restaurants and wine bars, and many offer tastings connected to the farm. Official sales statistics from Systembolaget show a rapid uptrend from 2015 to 2023, with sales volumes increasing by 482% and revenue by 633% over the period (Fig. 5). The total wine production was in 2024 estimated to around 300 000 litres (PIWI International, 2024). High labour costs in Sweden, combined with relatively limited yields due to climate and a short growing season, result in high bottle prices, necessitating a focus on the premium market segment (Mårtensson et al., 2013). Notably, Swedish consumers are willing to pay a premium for sustainably produced agricultural and horticultural products (OECD, 2018; The Swedish Board of Agriculture [SJV], 2024). This is a factor that can be utilised to create added value for Swedish wine.

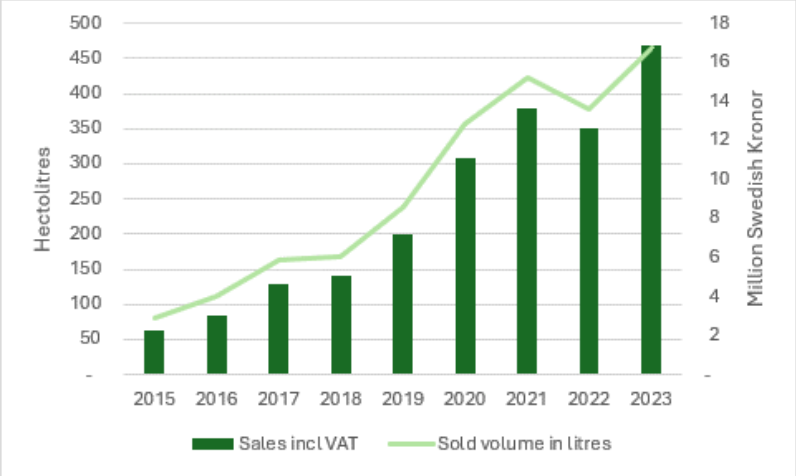

Figure 5. Sales volume and revenue of Swedish wine at Systembolaget, 2015–2023. *Data and Graph Source: Systembolaget.*

Farm sales of wine were not allowed in Sweden until 2025, when a new regulation was implemented in June of that year (Folkhälsomyndigheten, 2025). Although the new rules have met some criticism for being overly complicated and too strict, the introduction of farm sales is largely welcomed by wine farmers and is expected to increase profitability, stimulate rural tourism and the local economy, and attract new investments into the sector (Lantbrukarnas Riksförbund, 2025a; 2025b).

3.3 Geographical and climatic characteristics of the emerging Swedish wine production

Sweden, situated between 55° and 70° N latitudes, is located well outside the traditional winegrowing range, which typically falls between 30° and 50° latitude, both north and south of the equator (WSET Global, 2021). Most of the Swedish vineyards are located along the west and east coasts in the southern part of the country (Fig. 6), with around 80% of them concentrated in the southernmost county, Skåne (PIWI International, 2024). However, vineyards exist in 15 of the 21 Swedish counties, with the currently most northerly commercial vineyard located in the county of Södermanland at 59° latitude (Hallvarsson & Halvarsson, n.d.).

While Swedish wine production is increasing, the global wine industry is facing many challenges. The International Organisation of Vine and Wine (OIV, 2024) states that 2023 saw the lowest global wine production since 1961, due to several of the world's important wine regions facing adverse climatic events, such as early frost, heavy rainfall and drought, together with widespread fungal diseases. Climate change is projected to further increase the frequency of weather extremes (van Leeuwen & Darriet, 2016; van Leeuwen et al., 2024). Moreover, higher temperatures trigger earlier grape ripening, which in warmer regions risks negatively impacting the wine quality and style. In contrast, increased mean temperatures could present an opportunity for Swedish wine farming. According to van Leeuwen et al. (2024), climate change may lead to shifts in wine production geographies, where wine regions in colder climates, such as South Scandinavia, may see an increased suitability.

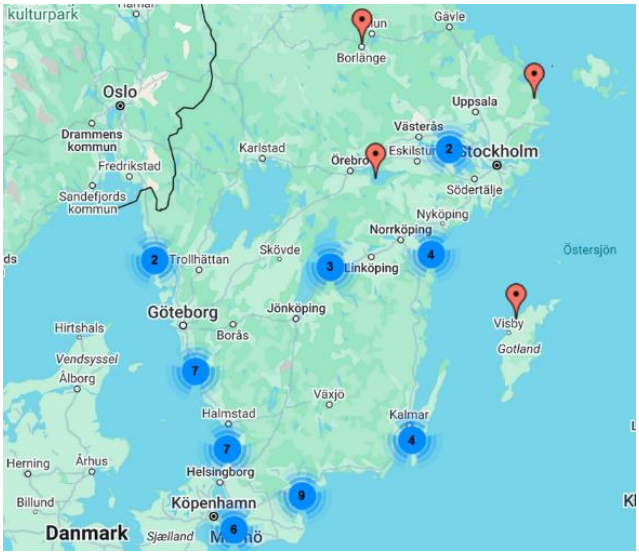

Figure 6. Map of vineyards in Sweden. This map, while not entirely current, illustrates the general distribution of vineyards, primarily along the southern coasts. Blue circles indicate clusters of vineyards, with the number representing the count within each cluster. *Source: The Swedish Wine Association (https://svensktvin.se/). Maps Data: ©2025 GeoBasis-DE/BKG (©2009), Google.*

Sweden's climate and photoperiod range (civil twilight to civil twilight) varies substantially from north to south. The photoperiod varies from 7 to 17 hours throughout the year in the southern part of the country (Fig. 7), while the northern part experiences polar night during parts of December until the first days of January, and midnight sun during the latter part of June and July. Annual precipitation ranges from 500 to 800 mm in southern Sweden. Traditionally, Sweden experienced four distinct seasons. However, climate change has led to noticeable shifts. In recent years, particularly in the southern coastal regions, the transition has often been directly from metrological autumn

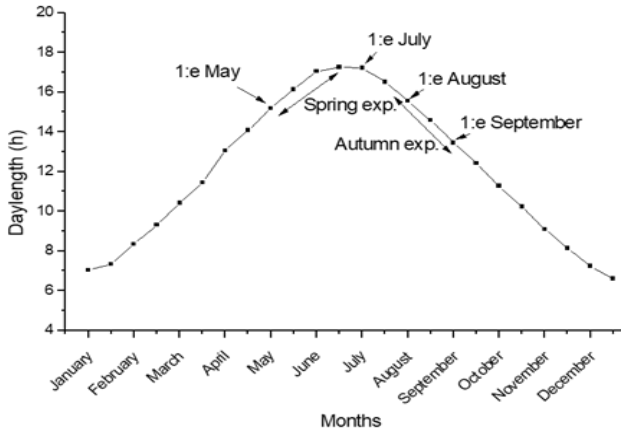

Figure 7. Photoperiod range (civil twilight to civil twilight) in the southern county of Sweden, Skåne (city of Lund). *Source: Nordmark, L*

to metrological spring without the intermediate period of metrological winter. Rising greenhouse gas concentrations contribute to increased temperatures, with Sweden experiencing a faster rate of warming than the global average, especially during winter (Sjökvist et al., 2025). Furthermore, the mean winter temperature in the Skåne coastal region was above zero degrees Celsius during the reference period 1971 to 2000 (Sjökvist et al., 2025). The average yearly temperature in the southern part of the country is approximately 8°C, with temperatures ranging between ±0 to 2°C during the coldest months (January and February) and temperatures ranging between 17 to 18°C during the warmest months (July and August), resulting in a vegetation period longer than 220 days (>4°C) (SMHI, 2024). According to Sjökvist et al. (2025) development is in line with Jones & Schultz (2016) description of the wine industry's expansion into new wine regions outside traditional winegrowing areas in both the northern and southern hemispheres. Moreover, it provides an interesting development of Winkler et al.'s (1974) description regarding Germany as the northernmost wine industry globally and highlights the rapid impact of climate change.

As shown in Figure 8, the growing degree-days (GDD) varied between 882 and 1136 over the documented period. According to Winkler et al. (1974), this range of GDD corresponds to the lower limit for grapevine production and aligns with Jones's (2006) categories based on the average temperature during the growing season (April-October for the Northern Hemisphere and October-April for the Southern Hemisphere). Overall, this establishes Sweden's status and recognition as a nascent wine region with potential, particularly in relation to the increasing mean temperatures. Some years exhibited greater deviations, particularly 2018, which recorded a significantly higher GDD. Continued GDD recordings are important for monitoring the ongoing development in the context of climate change and to provide explanations for annual variations. These measurements, combined with other tools, can aid producers in the development of more sustainable Swedish viticulture.

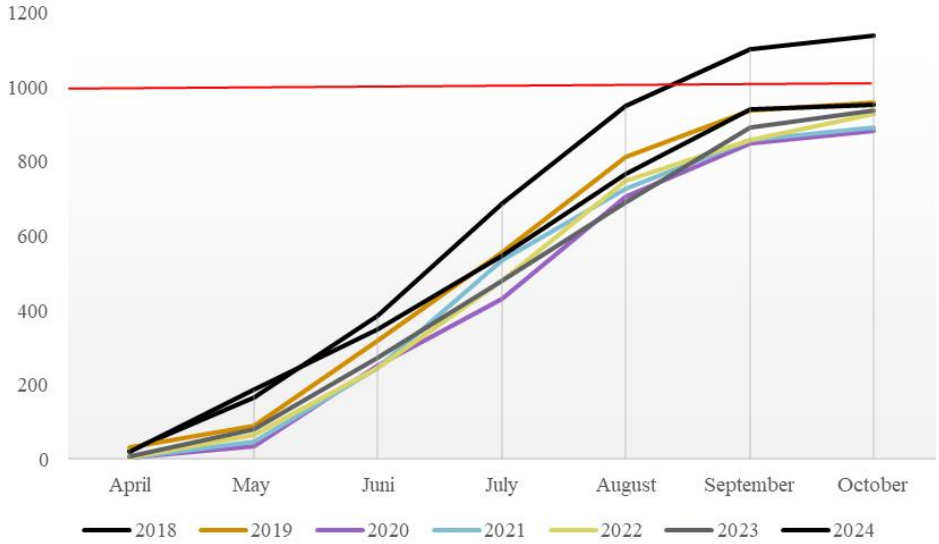

Figure 8. The diagram summarises daily growing degree-days (GDD) at Kullabergs Vineyard (Kullabergs Vingård) from April 1st to October 30th, between 2018 and 2024, showing a variation of 882-1136 GDD across those years. *Source: Nordmark, L.*

3.4 Grape varieties for a cold climate and a Swedish variety trial

All grape varieties permitted for wine production within European wine legislation are allowed in Sweden (Systembolaget, n.d.). To partly explain the recent success of Swedish wine production, a number of early-maturing fungal-resistant grape varieties have been introduced to the country, mainly so-called PIWI grape varieties (short for pilzwiderstandsfähige Rebsorten; German for "fungus-resistant grape varieties"). Several of these grape varieties, bred in Germany, Switzerland, and Austria with the aim of decreasing pesticide use, have proven suitable for Swedish conditions. Some examples that can be found in Swedish vineyards are Solaris, Cabernet cortis, Rondo, Regent, Souvignier gris, Donauriesling and Muscaris. Today, the PIWI variety Solaris (Fig. 9) is by far the most planted grape variety in Sweden (PIWI International, 2024; Systembolaget, n.d.). Solaris has proven suitable for producing aromatic grapes that are well-suited for quality wine production (Nordmark et al., 2016; Fabó, 2024). It is regarded by the growers as quick-developing, healthy, reliable, and suitable for various wine styles. A few traditional varieties, such as Pinot Noir, Chardonnay, and Pinot Meunier, are also used to a limited extent in Swedish vineyards.

Figure 9. A close-up of a ripe cluster of Solaris grapes in Lottenlund Estate, Skåne. Solaris, a fungi-resistant, early-maturing PIWI variety, is currently the most widely planted grape variety in Sweden. *Photo: Lottenlund Estate*

To enhance diversity and resilience against climate variations and plant pests, it is important to investigate and expand the range of grape varieties (Carbonell-Bejerano et al., 2015), as well as to identify optimal variety/rootstock combinations for consistent annual harvests in the Swedish climate. These efforts build upon existing cultivation knowledge. In the grape variety pilot trial including red and white fungus-resistant PIWI varieties presented in Figure 10 and 11, the achieved sugar content (°Bx) was analysed at harvest as a measure of maturity. Due to the annual variation observed in the pilot trial, only trends could be assessed (Fig. 10). The ANOVA did not show any significant differences in Brix levels between the varieties nor between red and white grapes. Nevertheless, there was a difference between the standard deviations, which may indicate the stability of a variety and should be taken into consideration. Moreover, all varieties consistently produced a ripe harvest at the beginning of the harvest window, even though red grapes in general require a longer ripening period (Skelton, 2020). This result suggests that new red fungal-resistant grape varieties could be grown on a larger scale in Sweden. However, our current experience is that white grape varieties have greater potential to achieve sugar levels where the addition of sugar (chaptalisation) prior to fermentation can be excluded, especially when growing varieties that yield grapes with an early sugar storage, such as Solaris (Nordmark et al., 2016).

Significant differences in harvest yields were recorded among grape varieties (Fig. 11), with both red and white varieties exhibiting notable variations. However, the yields were consistently lower than what is typically expected in traditional wine regions, which may be due to climate factors that are of the same importance as for all grape varieties grown at their northern border. No winter damages were observed on the plants. All in all, the results indicate that with the introduction of new PIWI varieties and rising average temperatures, there is an increased potential also for producing red light wines, at least in the southern coastal regions of Sweden.

The pH was not measured at harvest time in this pilot trial, given the assumption of sufficient acidity in this northern climate. Furthermore, optimal harvest time was not taken into consideration for each variety. It would have been beneficial to also have included Solaris as a reference. The outcome of this pilot trial will be used to guide deeper studies on the better-performing varieties. Further studies of harvest yield are needed, including the interaction between variety, clone, rootstock, soil health, and cultivation management (Van Leeuwen et al., 2016). Based on these results, it would be interesting to investigate the plants' ability to store carbohydrates for the following year and bud initiation. Considerable improvements could be achieved with increased knowledge of the growth and development stages of these varieties in relation to growing season temperature sums, total global radiation, and by prolonging the growing season through sustainable cultivation management. The goal is to use new knowledge about the regions' terroir in combination with an increased understanding of cultivation management to achieve more marketable harvests of up to 3 kg of grapes per plant without reducing the grapes' aromatic palette and sugar content.

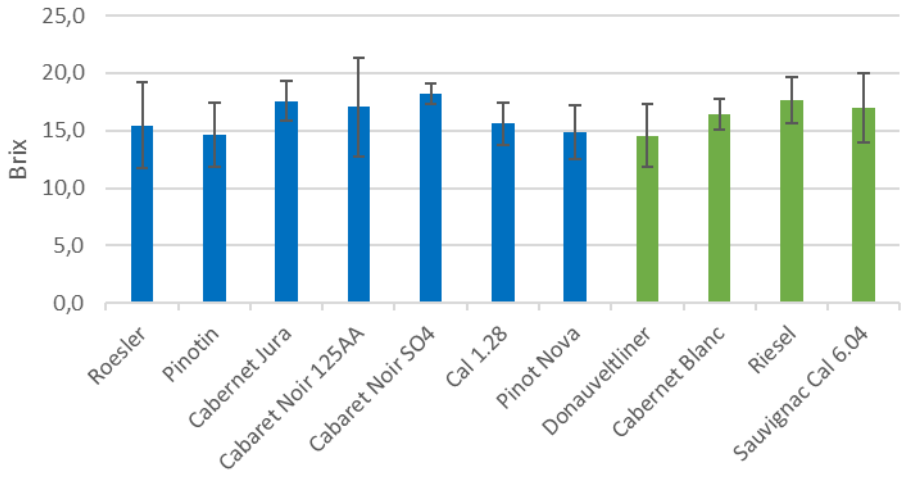

Figure 10. Sugar content (°Bx) at harvest for red and white grape varieties from a pilot trial conducted between 2021 and 2023. The graph shows a variation of °Bx levels across the years, but no significant difference was found between red and white grapes. *Source: Nordmark, L.*

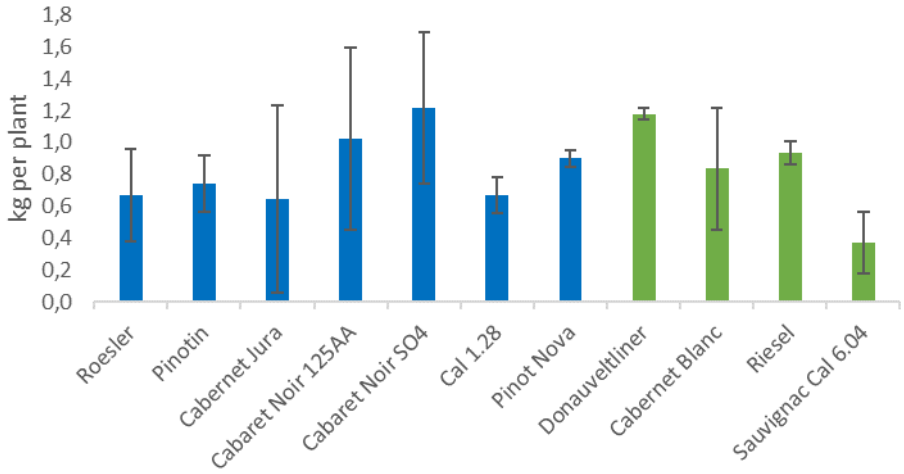

Figure 11. Harvest yield per plant (kg/plant) for red and white grape varieties from a trial conducted between 2021 and 2023. Significant differences in yield were recorded between varieties. *Source: Nordmark, L.*

3.5 The relevance of sustainability for Swedish cultivation and food production

Sweden has a long tradition of (comparatively) sustainable agriculture and horticulture (SJV, 2024; OECD, 2018; Formas, 2020). Swedish legislation regarding food safety, environment and animal welfare is in many cases stricter than the EU requirements. It is the country in the EU with the lowest use of antibiotics in animal production. Sweden benefits from a cold climate that naturally lowers plant pest pressure (SJV, 2024). Combined with strict environmental regulations on pesticide use, this has resulted in the country having among the lowest pesticide usage per cultivated area in the EU. Another example of early environmental initiatives in Sweden is that the country, for decades, has successfully implemented strategies to reduce nutrient leaching from agriculture (OECD, 2018; Fölster et al., 2012).

Although it should be mentioned that a milder and more humid climate and absence of long cold periods due to climate change can likely lead to better conditions for crop pests, pathogens and insect vectors to thrive (Roos et al., 2011). A good example is the recent concern regarding the spread of the grapevine leafhopper, the vector of grapevine Flavescence dorée (FD), into new geographical areas. This is particularly concerning as there are currently no practical alternatives to the use of insecticides for vector control (OIV, 2025).

An interesting feature of the Swedish legislation is that no copper-based pesticides are registered for use (Tamm et al., 2022; Hansson, 2020), forcing wine farmers to rely on alternative methods, such as the use of fungus-resistant grape varieties, alternative plant protection products and careful leaf thinning. Copper-based pesticides are widely used globally in both conventional and organic wine farming to combat bacterial and fungal plant diseases. This can be traced back to 1880, when Pierre-Marie-Alexis Millardet discovered the effectiveness of "Bordeaux mixture" ($CuSO_4$ + $Ca(OH)_2$) against downy mildew (*Plasmopara viticola*) (Neaman et al., 2024). In recent times, concerns have been raised regarding the adverse

effects of copper accumulation in soils, such as toxicity to soil organisms and young vines, stemming from copper-based pesticides. Ballabio et al (2018) found in their research on the copper levels in the soils of 25 countries in the European Union that, among land uses, vineyards have the highest Cu concentration.

Despite robust environmental policies and progress in the sustainability of Swedish food production, crucial challenges remain in aligning crop production with national sustainability goals as well as the global Sustainable Development Goals (SDGs) as outlined in Agenda 2030 (Formas, 2020; Kuylenstierna et al., 2019). In 2016, the Swedish government presented a National Food Strategy, emphasising applied and needs-driven research to support environmentally sustainable and competitive food production (Swedish Gov. Bill, 2016/17:104). Furthermore, the current Swedish strategy to implement the EU's Common Agricultural Policy (CAP) has a strong focus on sustainability, with 30% of the EU financial contribution allocated to support environmental and climate objectives (European Commission, 2023). This includes carbon sequestration, biodiversity, and the protection of valuable grasslands, as well as increasing knowledge in sustainable production.

3.6 Building a new wine region – a possibility to set high sustainability standards

As viticulture expands into new regions, it is essential to consider and mitigate negative impacts on natural ecosystems and biodiversity (Alexander et al., 2016; van Leeuwen et al., 2024). The expansion might otherwise risk leading to habitat fragmentation, soil degradation, and increased water consumption. Sustainable solutions emphasise avoiding the conversion of wild lands to preserve natural habitats, maintaining ecological balance and maximising ecosystem services. In Sweden, there is an opportunity to tap into the long tradition of sustainability in the country, as well as the national ambitions to further transition agricultural production with national and global sustainability goals. While a lot of crucial know-how is being brought from traditional wine countries, Sweden, as a young wine country, simultaneously benefits from an atmosphere of creativity since there is a need to find the best practices for the local climatic and environmental conditions (Fabó, 2024). Notably, many Swedish wine farmers already implement important methods for a sustainable production (where, e.g. Fig. 3, Fig. 4, Fig. 9, Fig. 12 serve as some examples).

Environmentally friendly production methods are often emphasised by the winefarmers themselves. Beyond a widespread use of fungus-resistant grape varieties, which are bred to decrease the need for pesticides, many of the vineyards maintain vegetation as ground cover and exclude the use of agrochemicals. Cover crops have been shown to provide several environmental benefits, for example, improvement of soil properties and water availability, increase biodiversity and reduce erosion as well as greenhouse gas emissions (Abad et al., 2021).

Figure 12. Kullabergs Vingård, in Skåne, Sweden. An example of the sustainability ambitions of many Swedish vineyards, here visualised in the ground cover. More than utilizing cover crops to promote soil health, they exclusively work with fungi resistant PIWI grape varieties, to limit the need of pesticide applications. *Photo: K-J Fabó*

As a young wine country, Sweden lacks regional or national wine laws (beyond the general European wine legislation) analogous to those found in many traditional wine-producing countries (e.g., the French AOC, the Italian DOC, and the Spanish DO). Such wine laws (appellations) often play an important role in preserving traditions, protecting quality, and guiding consumers. Appellations commonly regulate many aspects of wine production, for example, allowed cultivars, plant density, maximum allowed yield, pruning methods, and irrigation practices. While this can aid wine growers in decision-making, it has been shown to create obstacles for the wine industry's transition to sustainability (Reinhardt et al., 2024; van Leeuwen & Darriet, 2016). The absence of such in Sweden allows flexibility to develop locally adapted and optimised production practices. Moreover, if regional or national wine laws are established in Sweden, it can be a unique opportunity to include sustainability principles from the start.

The recently established Newclim project is an international academic collaboration featuring Sweden. It comprises the Swedish University of Agricultural Sciences (SLU), L'Institut Agro in France, Weincampus Neustadt in Germany, and Universidad de Chile. The aim is to support climate transition and sustainable practices in agriculture, focusing on perennial crops such as grapevine and apple (Newclim, n.d.). In recent emerging wine regions, such as the United Kingdom, academic research has proven crucial for industry success (NIAB, 2024; Vineyard Magazine, 2021). Although some initial research has been performed and Sweden is part of international collaborations, the country currently lacks dedicated viticulture and oenology research facilities. However, continued growth of the Swedish wine industry will require a similar level of

research support. The opportunity to undertake sustainability-oriented studies in younger wine industries, which so far have received limited coverage, has recently been highlighted (Engström et al., 2025).

3.7 Holistic, sustainable and climate-resilient approaches to viticulture

A comprehensive ecosystem-based approach connects viticulture to broader environmental and socioeconomic issues (Alexander et al., 2016; Némethy et al., 2016). By prioritising ecosystem services such as biodiversity, soil stability, and carbon sequestration, the resilience of vineyard landscapes is enhanced, making them more adaptable to climate change. Collaborative governance among farmers, researchers, and policymakers promotes social equity and long-term development. Designing new vineyards to be dry farmed wherever possible further protects water resources and supports climate resilience. Integrating sustainability principles and environmental stewardship into vineyard planning ensures long-term viability by supporting biodiversity and minimising ecological disruptions through techniques such as agroforestry, cover cropping, and wildlife corridors, ultimately benefiting both agriculture and the environment.

Given Sweden's strong sustainability ambitions (Swedish Gov. Bill, 2016/17:104; European Commission, 2023) and the pressing global environmental and climatic challenges (FAO, 2018), a strong emphasis on sustainability research is crucial to assist the emergence of the new wine region. In this context, the usefulness of highly sustainability-oriented approaches to viticulture could be thoroughly explored to examine their usefulness in the Swedish context. Two concepts in line with this are elaborated below: 'Regenerative viticulture' and 'Multifunctional agriculture'.

Regenerative viticulture

In recent years, regenerative farming has gained increased interest among practitioners, scientists and policy makers (Moyer et al., 2020; Noble Research Institute, n.d.; Masterson, 2022). The term 'regenerative organic agriculture' was coined by Robert Rodale, son of American organic pioneer J.I. Rodale (founder of Rodale Institute), in the 1980's to distinguish an approach to farming that goes beyond being simply 'sustainable' (Moyer et al., 2020). Rodale Institute describes the concept: *"Regenerative agriculture is marked by working to achieve closed nutrient loops, reduction or elimination of biocidal chemicals, greater crop and biological diversity, fewer annuals and more perennials, and practices that mimic natural ecological processes."* (Moyer et al., 2020).

Advocates of regenerative agriculture emphasise the possibility of achieving continuous net positive environmental effects, while simultaneously achieving high yields and revenues (Moyer et al., 2020; Noble Research Institute, n.d.; Masterson, 2022). Moreover, the goal is to turn agriculture into a mitigator of global warming instead of a contributor by implementing methods that sequester significant amounts of CO_2 from the atmosphere. In a review article by Villat & Nicholas (2024), the grapevine is highlighted as an especially suitable crop to support soil carbon sequestration, due to its perennial nature. They found the following measures to contribute to this goal: agroforestry, cover cropping, legume cover cropping, animal integration, non-chemical fertiliser, non-chemical pest management, and no tillage. In addition, O'Brien et al. (2025) highlight that regenerative viticulture methods support soil and biodiversity regeneration, land cooling, ecological enhancements, and soil water holding capacity.

Seven principles for regenerative agriculture are outlined by Rodale Institute (Moyer et al., 2020): (1) Diversifying crop rotations (2) Planting cover crops, green manures, and perennials (3) Retaining crop residues (4) Using natural sources of fertilisers, such as compost (5) Employing highly managed grazing and/or integrating crops and livestock (6) Reducing tillage frequency and depth (7) Eliminating synthetic chemicals. Notably, all these principles apply to wine farming, except for crop rotation (when not considering the rotation of cover crops). The challenge lies in how to optimise their application for local Swedish wine farming circumstances, such as selecting appropriate cover crop species and determining the best substitutes for agrochemicals, as well as establishing effective methods to monitor the effects of the measures taken.

The strong focus on soil health in regenerative farming is confirmed by a comprehensive review by Newton et al. (2020). Moreover, Moyer et al. (2020) state: "Regenerative agriculture is a systems approach to farming that builds soil health by supporting biodiversity above and below ground to return carbon and nutrients back to the soil.". This focus is especially interesting for wine farming, considering its focus on terroir, and particularly soil characteristics. Beyond geological properties of the soils, the biological characteristics and their influence on terroir are increasingly focused on in wine science through the concept of 'Microbial Terroir' (Liu et al., 2019; Gobbi et al., 2022).

Multifunctional agriculture

A concept that integrates environmental as well as socioeconomic aspects of agricultural practices is that of 'Multifunctional Agriculture' (MFA). The importance of MFA has been recognised for the prosperity of rural and peri-urban areas across diverse regions around the world (Zasada, 2011; Van Huylenbroeck et al., 2007; Zhang et al., 2023). MFA was recently highlighted at 'Tokaj Wine Congress 2024' with its holistic, sustainable, and transdisciplinary approach to viticulture (Némethy & Kreidlmayer, 2024). The OECD (2001) defines the concept as: *"Beyond its primary function of supplying food and fibre, agricultural activity can also shape the landscape, provide environmental benefits such as land conservation, the sustainable management of renewable natural resources and the preservation of biodiversity, and contribute to the socioeconomic viability of many rural areas."*

The vitality of Swedish rural areas is crucial for achieving sustainable food production and food security (European

Commission, 2023; Swedish Gov. Bill, 2016/17:104). Wine farming has been highlighted for its potential to increase rural tourism and create more job opportunities per hectare compared to other cultivations like cereal production (Hansson, 2020; Livets Goda, 2021; Lantbrukarnas Riksförbund, 2025a). Furthermore, as highlighted earlier, sustainable wine farming practices can positively impact the environment of agricultural landscapes. Conversations with Swedish wine farmers reveal that relying solely on wine sales is currently challenging, partly due to high production costs and moderate harvest yields. In this context, the MFA-concept can have important implications for agricultural and rural planning, policymaking, and support systems.

The entrepreneurial spirit among Swedish wine farmers is notably high, and producing wine is frequently combined with other wine-related offerings such as tasting events and guided tours, others produce and sell spirits, or run restaurants and hotels in conjunction with their vineyards. The concept of multifunctional agriculture is commonly associated with income diversification (Van Huylenbroeck et al., 2007; Zasada, 2011; Némethy et al., 2016). It has been shown that Dutch farmers implementing aspects of MFA are making increasing revenues from extra on-farm services, such as farm sales, green care, agri-tourism, child day care, nature conservation and education (Wageningen University & Research, 2025; Meulen et al., 2025). As noted by Némethy et al. (2016), the grapevine is a multifaceted plant with the possibility to deliver a range of products, beyond wines, fresh grapes, and raisins, including, for example, grape juice, strong spirits, grape seed and grape skin flour, grape seed oil, marmalades, and jellies. While some wine farmers in Sweden already produce strong spirits from grapes, and perhaps a few other grapevine-related products, there is likely room for a higher degree of product diversification, utilising the full potential of the grapevine, especially if the sector is supported by research, innovation, and entrepreneurship-encouraging policies.

4. Conclusion

The Swedish wine production is still small, but an emerging sector, which has already demonstrated the ability to produce appreciated wines of high international standard. Moreover, there is a predicted increase in suitability with a future warmer climate. An important factor for the current success has been the introduction of a number of cold-resistant and early-maturing grape varieties, which have proven suitable for Swedish conditions. Today, the vineyards are mainly planted with fungal-resistant PIWI grapes, primarily Solaris appreciated for its reliability and suitability for different styles of wines. As indicated by the variety trial included in this article, it is likely to find additional suitable varieties for wine production, both white and red, for southern Sweden. Moreover, a lack of a long wine tradition and the absence of rigid wine laws create both a need and an opportunity to find the most suitable methods for the local conditions of this young wine region. This should be developed within a sustainability context, given the country's long tradition of relatively sustainable food production, strict national pesticide regulations, and the global call to adapt food production to the Sustainable Development Goals. Caution must be taken in relation to the possible spread of currently non-existent grapevine pests and insect vectors due to a warmer climate. Since Swedish commercial wine farming is a very young endeavour, the scientific research and literature on the topic is very limited, and research is basically needed regarding all aspects of wine farming to support a growing industry. Here, we especially highlight the need for further grapevine trials to support adaptability to local environmental conditions and to further increase diversity and resilience against challenges such as climate variations and plant pests. Moreover, to support a sustainable viticulture expansion, we suggest further investigation into concepts such as regenerative viticulture - with its focus on soil health and benefiting environmental parameters without compromising yield - and multifunctional agriculture, which holistically addresses the environmental, social, and economic aspects of sustainability.

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