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Review

Lebanese Vitiviniculture at a Crossroads: Grapevine Diversity, Terroir, Sustainability, and Climate Resilience in a Mediterranean Wine Sector

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Highlights

What are the main findings?

- Lebanon combines exceptional grapevine genetic resources, altitudinal terroirs, and microbial diversity that remain underused in wine differentiation.
- Climate, water, sustainability, and fragmented sector governance are central constraints on future viticultural resilience.

What are the implications of the main findings?

- A national terroir framework linking germplasm, climate, vineyard performance, and origin could strengthen evidence-based differentiation.
- Coordinated conservation, sustainability metrics, traceability, and territorial branding could improve resilience and competitiveness.

Abstract

Lebanon combines a long viticultural history with strong topographic, climatic, and biological diversity, yet its wine sector faces challenges related to identity, climate variability, water availability, environmental sustainability, market competitiveness, and institutional coordination. This review synthesizes archeological, agronomic, genetic, microbiological, environmental, economic, and tourism-related evidence to reassess Lebanese vitiviniculture within a Mediterranean context. Recent molecular studies reveal extensive underexploited grapevine diversity, including locally distinctive genotypes and intra-varietal variation in traditional cultivars. Research on Merwah-associated yeasts and traditional fermentations further suggests that biological distinctiveness extends from grapevine germplasm to fermentation microbiota. Lebanese vineyard studies also demonstrate sensitivity of yield and berry quality to weather variability, while life-cycle assessment identifies opportunities to improve environmental performance from vineyard to bottle. We argue that durable competitiveness is more likely to emerge from differentiation than production scale. A strategic pathway is proposed that integrates terroir characterization, grapevine conservation and evaluation, climate adaptation, sustainable vineyard and winery management, landscape and heritage valorization, and stronger collective governance. Priority research needs include a national terroir atlas, multi-site cultivar trials, long-term climate–vineyard observatories, standardized sustainability indicators, and stronger traceability and origin systems.

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1. Introduction

Wine occupies an unusual position in Lebanese agriculture. The country is neither a major-volume producer nor conventionally classified among the dominant "Old World" wine countries, yet grape cultivation and wine production are deeply embedded in its history, rural landscapes and Mediterranean connections. Archeological evidence from Tell el-Burak has provided direct evidence for Iron Age wine production on the Lebanese coast, strengthening the material basis for linking wine with Phoenician-period agricultural and technological practices [1]. Modern commercial viticulture was subsequently reshaped during the nineteenth and twentieth centuries through Jesuit and French influence, the introduction of foreign cultivars, phylloxera, political disruption and, after the civil war, rapid expansion in the number and diversity of wineries.

Lebanon's modern wine sector, therefore, encompasses several intersecting identities. It draws on an ancient eastern Mediterranean heritage, but much of its contemporary varietal portfolio and technical language reflects French and international models. It benefits from a strong image of the Bekaa Valley, but vineyards and wineries also occur in Mount Lebanon, northern districts and other emerging areas. It has increasingly rediscovered cultivars such as 'Obeidi' and 'Merwah', while 'Cabernet Sauvignon', 'Syrah', 'Cinsault' and other internationally familiar cultivars remain central to commercial production. This coexistence can be a strength, but it also raises a strategic question: what makes Lebanese wine distinct in a crowded global market?

Earlier sectoral studies described a rapidly developing but fragmented industry and emphasized the need for stronger coordination, updated information, professional training, appellation or geographical-origin mechanisms, quality assurance and long-term policy [2,3]. More recent research has broadened the scientific basis for addressing these questions. Genetic studies have revealed unexpectedly rich and underexploited Lebanese grapevine resources [4,5], while additional molecular surveys have documented autochthonous or locally distinctive genotypes at risk of genetic erosion. Microbiological work on 'Merwah' has demonstrated high diversity within native *Saccharomyces cerevisiae* populations and the potential selection of local starter cultures [6]. Environmental assessment has quantified improvement opportunities across the Lebanese wine life cycle [7], and vineyard research has begun to document relationships between weather variability, yield and berry quality under Lebanese conditions [8]. Foundational histories of wine and viticulture also situate the eastern Mediterranean within a much longer trajectory of domestication, exchange and cultural meaning [9–12].

These advances justify a new synthesis. A review of Lebanese wine should no longer be limited to history, production statistics, and winery counts. It should integrate viticultural biodiversity, terroir, environmental performance, climate resilience, cultural landscapes, consumer behavior, tourism and governance. Internationally, sustainable vitiviniculture is increasingly understood as a system linking environmental integrity, economic viability, social responsibility, product quality, cultural heritage and landscape values. Mediterranean wine regions also provide relevant comparisons because they face similar pressures of warming, water scarcity, rural restructuring, landscape change and the need to differentiate through place-based identity [13–15].

This critical narrative review evaluates the available evidence on Lebanese viticulture, focusing on grapevine genetic resources, cultivar and clonal characterization, site-specific

vineyard performance, grape and berry quality, fermentation microbiology, environmental sustainability, and adaptation to climatic and resource constraints. We distinguish findings directly demonstrated in Lebanese studies from observations derived from restricted case studies, comparative Mediterranean evidence, and research priorities that remain to be tested locally. This review first characterizes the scientific evidence base and its methodological limitations, then examines opportunities for coordinated research on germplasm conservation, cultivar–site matching, vineyard monitoring, water and soil management, integrated pest and disease management, and environmental performance. Heritage, wine tourism, geographical differentiation, and collective governance are considered only insofar as they support implementation or communication of scientifically documented viticultural attributes.

2. Review Methodology

This article is a critical narrative review, not a systematic review or meta-analysis. Two author-provided Scopus-derived bibliographic collections contain 26 distinct records published between 2012 and 2026. These records are a targeted bibliographic starting point, not an exhaustive search yield. Other references cited in this manuscript include primary studies, policy documents and the Mediterranean comparative literature.

Publications were considered for relevance to Lebanese grapevine genetic resources, vineyard performance, terroir, climate and water constraints, fermentation biology, sustainability and contextual sector development. Evidence was classified as direct Lebanese empirical findings, geographically or temporally restricted Lebanese case studies, Mediterranean comparative evidence, or author-proposed priorities. Study design, sampling, replication and transferability were considered qualitatively; no formal risk-of-bias score was assigned.

Critical Appraisal and Transferability

The literature was interpreted according to study design, geographical scope, sampling strategy, temporal coverage, analytical methods, replication, and relevance to Lebanese viticulture. Four evidence categories were distinguished: (i) primary empirical research conducted in Lebanon; (ii) geographically or temporally restricted Lebanese case studies; (iii) evidence from other Mediterranean viticultural systems used for contextual comparison; and (iv) hypotheses, research priorities, or management proposals advanced by the present review. These categories describe the provenance and transferability of evidence rather than constituting a formal quantitative quality score.

Molecular surveys provide direct evidence for genetic diversity within the sampled Lebanese grapevine material but do not, by themselves, establish national cultivar prevalence, field performance, drought tolerance, or wine quality. Vineyard trials and longitudinal observational studies offer more direct agronomic information, although interpretation depends on cultivar, site, management, years observed, and the degree of replication. Fermentation studies characterize microbial communities or strain properties under the conditions examined; they do not demonstrate persistent regional microbial signatures without independent multi-site and multi-vintage validation. Life-cycle assessment provides a quantitative assessment of environmental burdens within specified system boundaries, but estimates are sensitive to inventories, functional units, allocation, and packaging or transport assumptions.

Mediterranean comparator studies are used to identify plausible mechanisms and candidate adaptation strategies, not as proof that those strategies are effective under Lebanese soils, climate, cultivar portfolios, irrigation systems, or institutional conditions. Recommendations arising from this synthesis are, therefore, presented as testable priorities rather

than validated interventions. Where nationally representative or replicated Lebanese data are lacking, conclusions are restricted to the locations, cultivars, seasons, and production systems actually studied.

3. Viticultural Context and Quantitative Sector Profile

3.1. Historical Development of Grape Use and Winemaking

Prehistoric and early historical context: Grapevine use and wine production have deep roots in the broader Near East, but archeological evidence from neighboring regions should not be conflated with direct evidence from present-day Lebanon. Chemical residues interpreted as evidence of wine production in the Late Chalcolithic Near Eastern Highlands, and archaeobotanical studies of grape domestication, establish a regional technological and agricultural context rather than a continuous Lebanese production sequence [16–18]. Grape consumption also needs to be distinguished from wine consumption: grape pips and other plant remains may document the presence or use of grapes without independently demonstrating fermentation [17].

Iron Age coastal production: At Tell el-Burak, south of Sidon, a plastered installation interpreted as a wine press provides direct archeological evidence for specialized wine production in the territory of present-day Lebanon. Archaeometric investigation of its lime plaster identifies a deliberately manufactured construction material suitable for a processing installation [1]. The press provides stronger evidence for local production technology than generalized assertions about Phoenician wine trading. The interpretation should, nevertheless, remain specific: the installation establishes a production facility, not the scale of annual output, the varieties processed, or the drinking habits of the wider population.

Processing, storage and consumption: A historical account should distinguish the successive stages of grape harvesting, crushing or pressing, juice collection, fermentation, storage, transport and consumption. The Tell el-Burak evidence bears directly on the pressing and collection stages; the remaining steps can be discussed as part of broader ancient Mediterranean wine technology but should not be attributed to this Lebanese installation without site-specific evidence [1,9,10]. Likewise, wine containers and maritime exchange networks are relevant to circulation and consumption, yet the presence of containers alone does not establish their contents unless supported by residue analysis or other contextual evidence. This distinction between archeological observation and technological reconstruction is essential to a critical review.

Later historical periods: The Roman, Byzantine, medieval and Ottoman periods belong in the chronological narrative, but the currently cited Lebanese literature does not establish a continuous, period-by-period record of vineyard area, grape consumption, wine production or specific cellar techniques. Religious, commercial and agricultural practices may have changed substantially across these centuries. Rather than imply uninterrupted continuity, this review identifies the need for targeted archeological, textual and archival sources before making quantitative or technological claims about these periods [9–12].

Historical continuity and its limits: Historical accounts and modern genetic surveys indicate that family and village grape cultivation, including grapes used for fresh consumption and arak, formed part of the agricultural setting preceding the nineteenth-century commercial revival. Nevertheless, evidence for Ottoman-period vineyard acreage, the precise continuity of named cultivars, and prevailing vine-training methods remains fragmentary. The persistence of present-day traditional cultivars should not be interpreted as molecular proof that individual varieties were cultivated continuously throughout the Ottoman period [4,19].

Phylloxera and rootstocks—evidence by period: A FAO country account dates the onset of phylloxera in Lebanese vineyards to the 1930s and describes the early Tel Amara

soil laboratory's use of soil calcium carbonate analysis to guide rootstock selection. Other modern grapevine literature reports an earlier outbreak chronology; these differing dates should be checked against contemporary Lebanese records before a precise national onset year is asserted. A later Lebanese vineyard survey [3] identifies 41B and 1103 Paulsen among rootstocks encountered in West Bekaa and 110 Richter and 140 Ruggeri in North Bekaa. These are documented modern survey observations, not verified names of rootstocks first introduced during the historical phylloxera response. The available evidence likewise does not support a dated national shift from bush vines to trellising attributable solely to phylloxera.

Nineteenth and early twentieth centuries: Modern commercial vitiviniculture followed a distinct trajectory. Historical accounts associate the renewed organization of vineyards in the Bekaa with Jesuit activity and identify Domaine des Tourelles, founded by François-Eugène Brun in 1868, as an early commercial initiative. French and other Mediterranean influences contributed cultivars and production practices, while phylloxera and subsequent replanting altered vineyard material and management. These statements describe the emergence of the modern sector and should not be read as evidence of uninterrupted technological transmission from the Iron Age [2,3,20]. More detailed assertions about particular planting systems, fermentation vessels and equipment will require historical winery archives or technical descriptions.

Post-1990 expansion and technological diversification: Following the civil war, the Lebanese wine sector experienced the entry of new producers, a wider portfolio of cultivars and increasing use of modern cellar technologies. Sector surveys document the diversification of wineries and the importance of the Bekaa while also highlighting fragmented information and governance [2,3]. The transition is best understood as modernization alongside continued use of traditional practices, rather than a single uniform technological model. A comparison of traditional and modern vinification processes is developed in the winemaking section of this review.

Overall, the historical evidence supports a sequence of documented episodes and transformations, not a single continuous national tradition. Archeology establishes selected ancient practices; historical and archival accounts document the re-emergence of commercial viticulture; and contemporary surveys describe the modern sector. Keeping these evidentiary levels separate allows the cultural significance of Lebanese wine to be recognized without overstating what is currently known.

3.2. Quantitative Sector Profile

Quantitative descriptions of Lebanese viticulture must distinguish total grape cultivation from wine-grape production and wine-sector output (Table 1). FAOSTAT-derived series reported approximately 11,300 ha of harvested grape area and 165,700 tons of grapes in 2024, but these national agricultural indicators encompass grapes for multiple end uses and cannot be treated as wine-grape statistics [21,22]. The most detailed wine-grape-specific survey identified in the literature was undertaken in 2015 and reported 216 responding growers, approximately 2636.85 ha of wine-grape vineyards, and 54 commercial wineries [3]. The survey documented a strong concentration of sampled wine-grape area in the Bekaa Valley, although its geographical proportions and production capacity classes should be interpreted as historical survey estimates rather than current national statistics. An earlier OIV account estimated annual Lebanese wine output at about 80,000 hL [23]. Separately, customs-based trade statistics reported 5.957 million liters of exports under HS 2204 in 2024 [24]. These data refer to different years, units and statistical populations; moreover, HS 2204 includes categories beyond still table wine. Accordingly, the present review reports each estimate with its source and reference year rather than combining them into a single production–

export balance. Updated national statistics on wine-grape area, irrigation, cultivar shares and winery size remain a priority for evidence-based sector assessment.

Table 1. Quantitative indicators of Lebanese viticulture: source, year and comparability qualifications.

Indicator	Value	Reference Year	Source	Limitations/ Comparability
All grapes: harvested area	11,300 ha	2024	FAOSTAT series via Helgi Library/Terra Cultiva [21,22]	Includes table, raisin and wine grapes; not wine-grape area.
All grapes: production	165,700 tons (rounded)	2024	FAOSTAT series via Terra Cultiva [22]	All grape uses; not wine or wine-grape production.
Wine-grape vineyard area in surveyed holdings	2636.85 ha	2015 field survey	Mohasseb et al. (2020) [3]	216 responding growers; historical survey, not a verified 2026 census.
Surveyed vineyard growers	216 respondents	2015	Mohasseb et al. (2020) [3]	Respondents may operate multiple plots; not necessarily number of vineyard parcels.
Commercial wineries surveyed	54	2015 survey (reported in 2020)	Mohasseb et al. (2020) [3]	Excluded firms purchasing finished wine for bottling; historical.
Winery production capacity categories	45% <20,000 bottles; 23% 20,000–120,000; 30% 120,000–1,000,000; 2% >1,000,000	2015	Mohasseb et al. (2020) [3]	Shares of 54 surveyed wineries; capacity categories, not actual output.
Wine-grape vineyard distribution	West Bekaa 56%; North Bekaa 26%; Central Bekaa 11%; Mount Lebanon 3%; North Lebanon 3%; South Lebanon 1%; East Bekaa 1%	2015	Mohasseb et al. (2020) [3]	Survey-based; percentages rounded and sum to 101%; no claim of current shares.
Wine-grape cultivars recorded	48 (22 white; 26 red)	2015	Mohasseb et al. (2020) [3]	Cultivar count in survey, not national inventory or area shares.
Wine output (historical estimate)	~80,000 hL/year	OIV report~2018	OIV [23]	Approximate historical estimate, not verified for 2024–2026.
Wine exports: HS 2204	US$20.77 million; 5.957 million liters	2024	World Bank WITS/UN Comtrade [25]	HS 2204 includes fortified wine and certain grape must; exports are not domestic production.

Table 1. *Cont.*

Indicator	Value	Reference Year	Source	Limitations/ Comparability
Wine exports: historical value	US$16.97 million	2020	LebTrade [25]	Historical export value; category and revisions must be checked before comparing with 2024.
Wine-grape irrigation share	Not verified	Current	No comparable national source established	Do not infer from all-crop irrigation data.
Current national wine-grape cultivar area shares	Not verified	Current	No comparable national source established	Survey frequency of cultivars does not measure planted area.
Current national winery count	Not independently verified	2026	Historical count in [3]; later secondary reports vary	Do not use approximate media figures as a census.

3.3. Economic Constraints, Export Performance and Sector Competitiveness

Economic interpretation requires a distinction between vineyard production, wine manufacturing, export trade and producer profitability. Lebanon-specific national data are not consistently reported for the same years, definitions or producer populations; consequently, grape area, grape tonnage, winery counts and export shipments should not be combined into a single measure of sector size. International merchandise trade data offer a reproducible but incomplete indicator of external market activity, not a direct estimate of domestic sales or winery value added.

According to the World Bank World Integrated Trade Solution (WITS), drawing on UN Comtrade, Lebanese exports classified under HS 2204 (wine of fresh grapes, including fortified wine, and specified grape must) were reported at USD 22.690 million and 6.128 million liters in 2023, compared with USD 20.770 million and 5.957 million liters in 2024 (Table 2). These correspond to changes of approximately −8.5% in declared value and −2.8% in volume. The implied unit values, about USD 3.70/L in 2023 and USD 3.49/L in 2024, are arithmetic trade-value ratios, not retail prices, winery margins or quality indicators. Reported export statistics can be affected by classification, reporting practices, re-exports and timing; a two-year comparison is insufficient to establish a long-term trend [24,26].

Table 2. Selected Lebanon wine-export indicators (HS 2204; reported merchandise exports; not wine production).

Year	Export Value (USD Million)	Quantity (Million Liters)	Implied USD/L
2023	22.690	6.128	3.70
2024	20.770	5.957	3.49

For 2024, the WITS identifies France (USD 3.472 million), Belgium (USD 3.382 million), the United States (USD 2.395 million), the United Kingdom (USD 2.381 million) and Norway (USD 1.617 million) among leading declared export destinations. Such market concentration may expose producers to exchange-rate, distribution, logistics and demand shocks, but concentration risk cannot be quantified without a complete multi-year destination series

and firm-level sales data. The designation of an export destination does not necessarily identify the country of final consumption [24].

Several constraints warrant analytical separation: (i) climate and water pressures affecting grape yields and production costs; (ii) fragmented or incomplete national data on vineyard and winery economics; (iii) input, energy, transport and packaging costs; (iv) access to finance and export distribution; and (v) traceability, cultivar authentication and evidence-based product differentiation. These are plausible pathways for research and policy analysis, not estimates of their relative contribution to producer losses. This review, therefore, recommends annual reporting of planted wine-grape area, harvested output, producer-level costs, ex cellar sales, export quantities and values by HS category, and destination market shares.

The financial and monetary crisis that began in 2019 requires explicit consideration when interpreting Lebanese winery competitiveness. Currency depreciation, restricted banking access and multiple exchange rate regimes may affect imported glass, closures, equipment, energy, working capital and domestic purchasing power differently. Export receipts denominated in foreign currency may partly offset certain costs for exporting firms, but neither a net benefit nor a uniform impact across producers can be inferred from aggregate trade data. Firm-level comparisons should record the currency and date of each transaction, imported-input shares, financing costs, energy expenditure, domestic/export sales composition and changes in real margins. These are hypothesized mechanisms and recommended variables, not quantified causal estimates for Lebanese wineries.

For export competitiveness, the 2023–2024 HS 2204 value and quantity series in Table 2 provide observable outcomes, but a historical revealed comparative advantage (RCA) calculation would additionally require Lebanon's total merchandise exports and comparable world wine and total merchandise exports for the same year and trade classification. An RCA value is, therefore, not reported without a fully matched dataset. Likewise, price premiums for verified Lebanese origin, indigenous cultivars or sustainability claims should be measured through choice experiments, revealed-preference data or matched-market transactions; the present literature does not justify assigning a universal premium percentage.

Lebanese consumer research provides a useful complement to the sector's production and export indicators. Koksal [27] examined differences among Baby Boomers, Generation X, Millennials and Generation Z in Lebanon, while a subsequent study [28] segmented Lebanese wine consumers by level of involvement. Together, these studies justify considering age cohort and wine involvement as distinct dimensions of market heterogeneity; they do not establish that generational preferences are fixed, that a given cohort consistently prefers indigenous cultivars, or that historical survey patterns remain unchanged in 2026. Economic disruption, purchasing power, availability, changing distribution channels and sample composition may alter observed preferences. Updated, representative surveys should, therefore, examine cohort and age effects separately and relate stated preferences to purchasing behavior, price sensitivity, origin information and willingness to pay. Claims that sustainability labels, heritage narratives or wine tourism generate a commercial premium require transaction evidence or appropriately designed consumer experiments rather than inference from cultural appeal alone.

4. Terroir, Geography and Vineyard Environments

Lebanon's physical geography is unusually compressed. Strong altitudinal gradients occur over short distances between the Mediterranean coast, Mount Lebanon, the Bekaa Valley and the Anti-Lebanon range. This creates marked variation in temperature, rainfall, solar exposure, soils and water availability. The Bekaa Valley remains the principal viticultural region and has historically supplied grapes to wineries located both within

and outside the valley. Yet the expansion of viticulture into higher-altitude and non-Bekaa locations has widened the range of Lebanese wine environments.

Terroir should be treated here as more than soil and climate. In contemporary wine research, terroir integrates environmental conditions with cultivar choice, management practices, historical continuity and human knowledge. For Lebanon, this broader interpretation is particularly useful because vineyard landscapes are products of repeated cultural transformations. Tannous's work on the Bekaa emphasizes vineyard typology, visibility, density, relief, built heritage and cultural routes as components of landscape value. Such elements can influence both regional identity and the visitor experience.

Older Lebanese studies already recognized the need to relate grape varieties and production practices more systematically to growing regions. Mohasseb et al. [3] documented a sector characterized by multiple production zones, numerous cultivars and heterogeneous winery–vineyard relationships. A future terroir strategy should move beyond generalized references to "Lebanese" or "Bekaa" wine and establish finer-scale agroecological characterization: elevation, slope, aspect, soil properties, temperature indices, water balance, phenology, cultivar performance and berry composition. This approach is consistent with integrated landscape analysis, in which ecological structure, historical change and human perception are treated as interacting dimensions rather than independent attributes [29].

Mediterranean comparisons demonstrate why this matters. Long-term analysis in Cyprus shows that viticultural landscapes can undergo cycles of expansion, contraction and spatial displacement as economic, demographic and environmental conditions change [30]. Climatic suitability modeling in Greece similarly illustrates that future viticulture cannot be planned solely from historical distributions. For Lebanon, where elevation offers potential thermal buffering, but water availability can be limiting, spatially explicit vineyard characterization is a priority.

Landscape also has ecological functions. Vineyards can either simplify or enrich rural mosaics depending on ground management, pesticide use, field margins, stone terraces, woodland retention and surrounding land cover. International research on sustainable and "heroic" viticulture has increasingly connected vineyard management with biodiversity, ecosystem services, erosion control, cultural heritage and tourism. These links are highly relevant to Lebanon, particularly where vineyards occur near traditional villages, natural areas, orchards and mountain habitats. Climate–quality studies from other wine regions further demonstrate that weather signals must be interpreted through cultivar and site, not used as universal predictors [31].

4.1. Wine-Growing Regions and the Limits of Existing Spatial Evidence

The available Lebanese winery survey identifies production and winery activity across the Bekaa, Mount Lebanon, northern districts and southern districts [3]. These are broad reporting regions rather than legally delimited appellations or homogeneous terroirs. The Bekaa must be further differentiated by subregion and site. Published regional maps and promotional inventories offer orientation but should not be interpreted as a georeferenced vineyard census. A scientifically reproducible map requires vineyard polygons or verified point locations, a stated observation year, and a transparent source for boundaries and elevation data.

A national spatial inventory should distinguish the location of wineries from the location of grape-producing parcels, because fruit may be transported across districts. At minimum, map layers should include administrative boundaries, a digital elevation model, slope and aspect, vineyard parcels, meteorological station coverage, annual rainfall and growing-degree-day surfaces, soil attributes, and water availability. Data resolution and

uncertainty should be disclosed; interpolated climate layers should not be presented as direct observations at individual vineyards.

4.2. Regional Differentiation and the National Terroir Atlas

Finally, regional differentiation can support a more nuanced national identity. A strong Lebanese wine brand need not imply uniformity. Many successful wine countries combine an overarching national reputation with recognizable regional and subregional identities. Lebanon could follow the same principle, provided that regional claims are evidence-based and supported by traceability. The long-term goal should be a nested identity: Lebanon as an eastern Mediterranean wine origin; scientifically characterized regions and landscapes within Lebanon; and individual vineyards or sites where evidence and market value justify finer differentiation. This would transform geographic diversity from a descriptive feature into a structured competitive asset.

The development of a national terroir framework should remain inclusive of both local and international cultivars. International varieties have contributed substantially to the reputation and commercial viability of modern Lebanese wine, and their performance across Lebanese environments deserves continued study. The opportunity is not to replace them indiscriminately, but to understand where they perform best and where local or regionally adapted material may provide greater distinctiveness or resilience. Experimental vineyards that compare cultivars and clones across representative Lebanese environments would provide evidence for this transition. Such networks could be coordinated among universities, LARI, growers and wineries and could become a long-term research infrastructure for the sector.

A terroir atlas would have practical value beyond academic description. Growers could use it to guide new plantings and cultivar selection; wineries could use verified site information in origin communication; tourism planners could identify coherent landscape units and routes; and policy makers could identify vineyards of cultural, genetic or scenic significance. Most importantly, such an atlas could connect several themes that are currently studied separately: climate adaptation, genetic resource conservation, wine quality, landscape protection and territorial branding. This integrative function is especially important for a small country where vineyard decisions, tourism development and urbanization often occur within the same landscapes.

Remote sensing and geographic information systems could accelerate this process. Satellite and drone imagery can support vineyard mapping, vigor assessment, land-use change analysis and identification of abandoned or old-vine parcels. When combined with ground surveys and genetic identification, spatial tools could help locate reservoirs of traditional germplasm that are currently absent from official statistics. They could also quantify threats from urban expansion, road development, wildfire and land abandonment. The long-term Cypriot landscape analysis of Papadias et al. [30] demonstrates the value of reconstructing viticultural change through space and time; a comparable Lebanese program could reveal where vineyards have persisted, disappeared or shifted and how those changes relate to markets, conflict, demography and environmental stress.

The Bekaa itself should not be treated as a single terroir. North, central, west and southern parts of the valley differ in elevation, rainfall, soils and exposure, and the existing survey literature shows differences in cultivar distribution and winery location. Mount Lebanon and northern wine-growing areas add still other combinations of slope, altitude and proximity to the Mediterranean. Future studies should use standardized descriptors across these regions so that comparisons become cumulative. Repeated measurements of budburst, flowering, veraison, harvest date, yield components, must composition and water status would allow researchers to distinguish persistent site effects from vintage effects.

Such data would also provide a stronger scientific basis for future geographical indications and for communicating regional differences to consumers.

The practical implication of this geographic heterogeneity is that elevation cannot serve as a proxy for viticultural suitability. Higher sites may offer cooler ripening conditions but can also face frost, shallow soils, exposure, erosion and constrained water access. Regional comparisons should, therefore, combine elevation with aspect, soil depth, water balance, cultivar and repeated phenological observations.

4.3. Comparative Regional Climatic Context and Limitations of Available Observations

Lebanese wine-growing environments should not be represented by a single national climatic mean. The rain shadow effect of Mount Lebanon, elevation, slope orientation and distance from the Mediterranean produce contrasting moisture and thermal regimes across the Bekaa and western mountain slopes. A recent Lebanon-focused hydroclimatic study describes the inland Bekaa as markedly drier than the coastal and southern climatic zone, reporting broad regional annual precipitation of approximately 200–450 mm for the inland setting versus approximately 700–1000 mm for the wetter coastal/southern setting. These figures characterize broad climatic zones rather than measured rainfall at individual vineyards and must not be used as interchangeable winery-level values (Integrating Meteorological and GRACE-Based Indices, 2026; full bibliographic details to be verified).

Table 3 summarizes the geographical differentiation that can be supported at present. Its purpose is to identify regional contrasts and the limits of the available evidence, not to imply a standardized climate-normal database for Lebanese wine regions. In particular, comparable regional mean annual temperatures, growing-season temperatures and growing-degree-day values could not be established from a consistent network of vineyard stations and reference periods. Reporting invented or mixed-period averages would be misleading. The site-based Lebanese Cabernet Sauvignon study by Ghantous et al. [8] provides stronger evidence that interannual weather variability is associated with yield and berry quality, but two study sites cannot define the climatic normals of all Lebanese viticultural regions.

The precipitation ranges describe broad national climatic zones and are not direct measurements for every listed region. Temperature values are intentionally not supplied where a common station network and reference period could not be verified. Data should be replaced or supplemented by 1991–2020 (or an explicitly identified alternative period) meteorological normals from named stations, with elevation, coordinates, missing-data treatment and distance to vineyard reported. (Sources: Ghantous et al. [8]; Mohasseb et al. [3]; Integrating Meteorological and GRACE-Based Indices to Assess Groundwater Drought Under Climate Change in Data-Scarce Mediterranean Basins (2026; bibliographic verification pending); Union Vinicole du Liban, Four Wine Regions of Lebanon (2023; descriptive sector source)).

For an operational terroir atlas, each sampling unit should include coordinates and elevation; daily minimum and maximum air temperatures; seasonal precipitation; growing-degree days with an explicitly stated base temperature; frost and heat-event frequency; reference evapotranspiration and irrigation supply; soil texture, depth and available water capacity; slope and aspect; and cultivar, rootstock, training system, phenology and harvest composition. These data should be collected over multiple vintages and analyzed with site and year treated separately. Regional classification must, therefore, be considered a testable hypothesis rather than proof of a fixed sensory or quality hierarchy.

Table 3. Evidence-aware comparison of Lebanese wine-growing environments.

Region/Subregion	Vineyard Setting and Climatic Interpretation	Precipitation Evidence	Temperature Evidence/Comparability
Northern/upper Bekaa (including Baalbek–Hermel)	Inland, relatively dry rain-shadow setting; elevation and local exposure vary	Broad inland climatic context: c. 200–450 mm/year; NOT a vineyard- or subregion-specific normal	Cooler winters and substantial seasonal contrast; no comparable site-based annual or growing-season mean verified
Central/western Bekaa (including Zahle–Ksara and surrounding vineyards)	High inland valley with strong site-to-site variation in slope, soil, aspect and irrigation access	No single verified common-period vineyard precipitation normal; do not apply northern Bekaa range indiscriminately	Temperature and vintage effects documented at selected Lebanese vineyard sites [8]; regional normals not established
Southern Bekaa/western foothills	Transition between inland valley and mountain-facing exposures; local rain-shadow gradients	Station-specific multi-year precipitation series needed	Station-specific minimum/maximum and growing-season indices needed
Batroun/northern coastal mountains	Sea-facing hillsides and inland high slopes; strong elevation and maritime exposure gradients	Do not equate coastal-zone precipitation averages with upland vineyard measurements	Marine influence and elevation may moderate heat differently by site; common-period station means needed
Mount Lebanon/other western highland sites	Steep topography, contrasting aspects and locally high-altitude vineyards	Broad wetter western/coastal climatic context cannot substitute for parcel observations	Elevation, frost exposure and diurnal range require on-site or gridded validation
Jezzine/southern highlands and emerging sites	Mountain and foothill mosaics; heterogeneous exposures and water availability	Insufficient harmonized wine-vineyard station normals identified	Insufficient harmonized wine-vineyard temperature normals identified

5. Grapevine Genetic Resources and Cultivar Characterization

The most important recent change in the scientific understanding of Lebanese viticulture concerns grapevine genetic resources. For many years, discussion of Lebanese wine identity focused on a relatively small set of named local cultivars, particularly 'Obeidi' and 'Merwah', alongside widely planted international varieties. Recent molecular work indicates that the underlying diversity is considerably richer.

Recent molecular investigations have substantially improved the characterization of Lebanese grapevine germplasm. Saliba et al. [19] analyzed 202 leaf samples collected from 101 locations using microsatellite markers and identified 67 distinct genotypes, of which 34 did not match the consulted reference profiles. Independently, Merheb et al. [4] collected 276 accessions, identified 102 distinct genetic profiles using nuclear SSR markers, and reported 63 profiles without matches in the reference databases. These studies provide direct Lebanese evidence of substantial underdocumented genetic diversity and demonstrate the importance of resolving vernacular name synonymy, homonymy, and misidentification. However, unmatched profiles should not be interpreted automatically as newly established cultivars, unique Lebanese endemics, or genotypes with proven agronomic superiority. The two studies should not be summed to estimate national cultivar richness because their sampling frames and genetic materials may overlap. A coordinated reference collection, standardized genotyping, ampelographic verification, and replicated field trials are needed

to link genetic identity with phenology, yield stability, disease response, water-use traits, and wine quality.

Khater et al. [5] add another level of complexity by demonstrating intra-varietal diversity within 'Obeidi', 'Merwah', 'Aswad' and 'Maryame'. Ampelographic and ISSR analyses of accessions from different agroclimatic areas revealed variability within named cultivars, particularly in bunch and berry characteristics. Such clonal diversity may be agronomically valuable because long-propagated cultivars can contain material differing in phenology, yield, berry traits and stress responses.

These findings have direct strategic implications. First, conservation should include field repositories, on-farm conservation and systematic documentation of old vines, not merely preservation of a few commercially recognized names. Second, agronomic evaluation must follow genetic identification. A genotype is not automatically suitable for quality wine; it must be tested for yield stability, phenology, disease susceptibility, drought response, must composition, sensory performance and compatibility with rootstocks and training systems. Third, the sector should distinguish between indigenous, historically established Mediterranean and recently introduced international cultivars rather than using "local" loosely.

'Obeidi' and 'Merwah' already offer an entry point for differentiated Lebanese wines, but the emerging germplasm evidence suggests a larger innovation pipeline. Underexplored white and red genotypes may eventually support niche wines, blends or climate adaptation strategies. This is particularly relevant because global viticulture is highly concentrated on a limited number of cultivars. Diversifying with well-characterized local material can simultaneously support biodiversity conservation and market differentiation.

Commercially Encountered, Traditionally Named and Newly Documented Cultivars

The available sources describe different populations and must not be combined as a single national ranking. The exploratory 2015 survey reported by Mohasseb et al. [3] recorded 48 wine-grape cultivars (22 white and 26 red). In descending order of occurrence across surveyed growing regions, the authors listed 'Cabernet Sauvignon', 'Syrah', 'Tempranillo', Merlot, 'Chardonnay', 'Viognier', 'Sauvignon Blanc', 'Cinsault', 'Grenache', 'Cabernet Franc', Muscat and Arinarnoa; less frequently encountered cultivars included 'Mourvèdre', Caladoc, 'Carignan', 'Pinot Noir', Clairette, 'Merwah', Petit Verdot, Sangiovese, Ugni Blanc, Carménère, 'Obeidi', Vermentino and Marselan. These are survey occurrence rankings, not percentages of planted area or an up-to-date national inventory. The same survey noted that local cultivars, including 'Merwah', 'Obeidi' and Meeseseh, were grown by a minority of responding growers [3] (Table 4).

Traditional names and genetic identities require separate treatment. Merheb et al. [4] identified 102 distinct SSR profiles among 276 collected accessions; the frequently recovered profiles in that deliberately targeted germplasm sample included Blanc de Dellys (reported synonym: 'Merwah'/Marouhé), Dabouki, Beitamouni, Sebai Assouad and Inab el Mir. The sample was enriched for old, abandoned and underdocumented vines, so these frequencies cannot estimate their prevalence in commercial vineyards. Saliba et al. [19] examined 202 grapevine leaf samples from 101 locations and documented 67 genotypes, further exposing the limits of vernacular naming. The identity, presumed origin and intended use of 'Obeidi', 'Merwah' and other names should be reported in relation to molecular reference profiles rather than inferred from names alone [4,19] (Table 5).

Table 4. Cultivar categories and strength of evidence in Lebanese viticulture.

Evidence Category	Documented Examples	Interpretation and Limitation
Commercial wine-grape survey (2015)	Cabernet Sauvignon; Syrah; Tempranillo; Merlot; Chardonnay; Viognier; Sauvignon Blanc; Cinsault; Grenache	Ordered by occurrence across surveyed regions, not by hectares; survey is not a 2026 census [3].
Additional surveyed wine cultivars	Cabernet Franc; Muscat; Arinarnoa; Mourvèdre; Caladoc; Carignan; Pinot Noir; Clairette; Petit Verdot; Marselan	Presence reported by survey; planting extent and introduction dates not established [3].
Traditional or locally documented material	Obeidi; Merwah/Marouhé; Beitamouni; Dabouki; Sebai Assouad; Inab el Mir; Meeseseh	Uses include table grapes, wine and arak; vernacular identity and provenance require genetic confirmation [3,4,19].
Genetically distinct but underdocumented accessions	63 previously unmatched profiles among 102 genotypes in the Merheb et al. [4] sample	Novel database profiles are not automatically new cultivars, commercially adopted or proven indigenous [4].
Documented pre-2016 introduction	Malbec in Bekaa vineyards by 2013	Evidence of introduction before the requested last-decade window; cannot date a 2016–2026 introduction [32].
Introductions during 2016–2026	Not reliably enumerated in the cited studies	Requires dated nursery import, planting and certification records; do not infer from present-day marketing.

Table 5. Comparative characteristics of Lebanese grapevine genetic surveys.

Study	Material	Genotyping	Findings	Interpretive Limit
Saliba et al. [19]	202 samples; 101 locations	21 microsatellite markers reported in abstract; 20 nSSR loci used in some analyses	67 genotypes; 34 unmatched profiles	Non-random collection; not a national census; agronomic traits not experimentally established
Merheb et al. [4]	276 collected accessions	22 nuclear SSRs and 3 chloroplast SSR markers	102 distinct profiles; 63 unmatched	Old/home-garden vines emphasized; identity does not establish cultivar performance

The category "newly introduced" also needs a time boundary. Ghantous et al. [32] described 'Malbec' as recently introduced in the Bekaa in a study involving vines present in 2013 and trials initiated in 2014; this supports introduction before, not necessarily during, 2016–2026. A separate examination of Ministry of Agriculture nursery-import registers for 2012–2014 documented substantial grapevine planting-material imports but does not establish cultivar-specific introductions in the last decade. Without dated nursery, registration or planting records, the review cannot reliably name or quantify cultivars newly introduced between 2016 and 2026. The appropriate next step is to reconcile annual import records, certified nursery catalogs, winery planting records and molecular verification.

6. Vineyard Performance, Phenology and Berry Quality

Lebanese viticultural research has begun to move from sector description toward experimental evaluation. Ghantous et al. [32] examined cultural practices affecting the recently introduced red cultivar 'Malbec' in the Bekaa, illustrating the need to adapt canopy and vineyard management to local conditions rather than simply importing cultivar management packages. More recently, Ghantous et al. [8] analyzed 'Cabernet Sauvignon' yield and berry quality in relation to weather variability over an extended period at two Lebanese sites. The study confirms that interannual weather variation can materially affect vineyard performance and reinforces the importance of site-specific climate monitoring.

For Lebanon, climate risk must be interpreted through strong altitudinal and regional gradients. The 'Cabernet Sauvignon' study by Ghantous et al. [8] demonstrates measurable relationships between weather variability and yield/berry quality at Lebanese sites, but the national evidence base remains limited. Long-term phenological and yield datasets are scarce, and systematic comparisons among indigenous and international cultivars are urgently needed.

Available Lebanese cultivar-specific observations should not be generalized to all varieties, sites or vintages. Replicated multi-site and multi-season evaluations are needed to assess phenology, yield, berry composition and water-use performance.

6.1. Cultivation Systems and Management Practices Documented in Lebanon

Lebanese survey-based details. Mohasseb et al. [3] reported a diversity of grafted rootstocks and vineyard planting densities, with 3000–5000 vines ha^{-1} common among surveyed vineyards, and lower-density or higher-density plantings in particular regions. These descriptive survey results help distinguish documented Lebanese practices from generic Mediterranean recommendations; however, the survey was not designed to estimate current national frequencies or to test causal effects of training and rootstock selection on yield or quality.

Lebanese wine-grape cultivation spans old, low-yielding mountain vineyards and managed commercial vineyards in the Bekaa. However, the available peer-reviewed literature does not provide a representative national census of vine-training systems, planting densities, rootstocks, pruning regimes, or mechanization. Consequently, the following examples should be read as documented site-level practices, not as nationwide frequencies. The study of 'Malbec' at Deir el Ahmar and Mansoura compared vines under contrasting site and management conditions, including canopy intervention and plant nutrition, illustrating that cultivar performance cannot be separated from management and environment [32]. Because these treatments were not independently replicated across a national network, their results should not be generalized to all Lebanese vineyards.

At the vineyard scale, relevant cultivation decisions include bush or head training versus trellised systems, winter pruning intensity, shoot positioning and leaf removal, soil cultivation versus seasonal cover, nutrient supply, and rainfed versus supplemental irrigation. These are established options in Mediterranean viticulture, but their distribution and comparative performance in Lebanon require field documentation. Any assessment should record cultivar and clone, rootstock, vine age, planting density, trellis geometry, pruning severity, canopy dimensions, irrigation volume, soil management, and pest control records together with yield and berry chemistry. Without such descriptors, apparent site differences may reflect management rather than terroir.

6.2. Vineyard-to-Winery Production Pathways

For still white wine, the principal process stages are maturity-based harvesting; sorting and, where appropriate, destemming or crushing; pressing, sometimes preceded by brief

skin contact; must clarification; alcoholic fermentation; optional malolactic fermentation; maturation; stabilization; filtration where used; and bottling. For still red wine, destemming/crushing is commonly followed by fermentation in contact with skins and seeds, with extraction managed by cap handling, maceration duration and temperature; pressing, malolactic fermentation, maturation and bottling follow. Rosé production may use short-time skin contact followed by pressing or direct pressing. These are general technological pathways rather than verified descriptions of every Lebanese producer; the selected yeast, vessel, temperature, sulfur dioxide regime and maturation strategy differ by winery and wine style.

A Lebanese case study provides more precise process-level evidence. In a traditional Mount Lebanon winery producing 'Merwah' wine, grapes from two mountain vineyards were assessed for sugar and acidity before harvest; crushed fruit underwent brief skin maceration; the must was fermented spontaneously in oak barrels at approximately 15–18 °C; and sulfur dioxide was applied at specified processing stages [6]. This is a valuable, documented example of white-wine technology, but it does not establish the prevalence of spontaneous fermentation, barrel use or those temperatures across Lebanon. In a subsequent pilot-scale study of 'Merwah', three selected indigenous *Saccharomyces cerevisiae* strains were compared with spontaneous fermentation during the 2019 vintage; only one strain dominated fermentation to completion, demonstrating the practical distinction between finding local yeast diversity and obtaining reliable starter performance [33].

Traditional cooked wines represent a distinct production pathway: grapes must be heated to concentrate sugars before spontaneous fermentation. A study of seven fermentations at four Lebanese wineries documented substantial variation in fermentation dynamics associated with initial sugar concentration [34]. These products should not be conflated with conventional dry red or white wines. Comparisons with Mediterranean and international production must, therefore, match the wine style, must composition, fermentation management and product specifications rather than assume that "traditional" and "modern" techniques are mutually exclusive.

6.3. Comparative Evidence and Technical Research Gaps

For a meaningful Lebanon–Mediterranean comparison, vineyard studies should report pruning and training system, vine water status, yield per vine and per hectare, cluster and berry traits, soluble solids, titratable acidity, pH and phenological dates using harmonized methods. Winery comparisons should report grape maturity, fermentation temperature, duration, vessel type, inoculation status, extraction regime, alcohol, volatile acidity, residual sugar, and sensory outcomes. The Lebanese evidence currently supports specific case studies rather than a national typology of cultivation and winemaking technologies. A multi-winery, multi-vintage survey combined with replicated cultivar × management trials is, therefore, a research priority, not a completed finding.

7. Abiotic and Biotic Constraints: Water, Soil, Pests, Diseases and Climate Adaptation

Lebanon's vineyards operate across pronounced altitudinal and topographic gradients, making local responses to climate variability potentially heterogeneous. National assessments identify increasing temperature, changes in precipitation and snow accumulation, and seasonal water stress as important climate-related concerns for agriculture and water management [NEW REF: Lebanon Fourth National Communication; NEW REF: Lebanon National Adaptation Plan]. However, these national assessments do not by themselves quantify changes in grapevine phenology, berry composition, yield, or irrigation demand in individual Lebanese vineyards.

The Fourth National Communication to the United Nations Framework Convention on Climate Change (submitted in 2022) presents observed and projected climatic risks, including agriculture and water resource vulnerability. The 2025 National Adaptation Plan (2025–2035) likewise identifies agriculture and water resources among its priority sectors and calls for coordinated monitoring and adaptation. These documents establish a defensible national context for viticultural risk assessment, but local vineyard responses must be tested against site-specific meteorological, soil, cultivar, and management observations.

Lebanon's long-term low-emission development strategy reports scenario-based reductions in annual water availability of approximately 5.7% under RCP4.5 and 9% under RCP8.5, alongside substantially greater dry-season reductions (42% and 54%, respectively). These figures describe modeled national water resource outcomes and should not be presented as direct measurements or predictions of wine-grape irrigation requirements. Their interpretation depends on the underlying scenarios, model assumptions, spatial aggregation, and assessment horizon [NEW REF: Lebanon LT-LEDS; check original underlying assessment and projection period before final citation].

For grapevines, plausible pathways of climate sensitivity include altered phenological timing, higher evaporative demand, changes in soil-water balance, and shifts in ripening conditions. The direction and magnitude of effects on yield, grape composition, and wine quality remain cultivar- and site-dependent. Consequently, this review does not infer that warming has already caused a uniform decline in Lebanese wine quality or that any particular altitude or cultivar offers proven long-term protection.

Priority Lebanese research should combine long-term weather observations with replicated, multi-vintage vineyard trials. Core measurements would include budburst, flowering, veraison and harvest dates; yield and berry composition; soil moisture; plant-water status; irrigation volume and water productivity; and disease or pest incidence. Trials should compare locally relevant cultivars and rootstocks across contrasting altitudes, soils and water management regimes. Deficit irrigation, mulching, soil cover management and cultivar selection should be described as candidate adaptations requiring local evaluation, not as universally validated recommendations.

Mediterranean research provides useful hypotheses. Costa et al. [13] describe water scarcity as a central vulnerability of southern European viticulture and emphasize integrated adaptation rather than irrigation alone. Lereboullet et al. [14] show that climate adaptation is socio-ecological: growers respond not only to biophysical change but also to institutions, knowledge, markets and perceptions. Recent research on the Cypriot cultivar 'Xynisteri' further illustrates the potential value of locally adapted root and stress response traits in eastern Mediterranean germplasm. Such findings should stimulate, not substitute for, testing of Lebanese cultivars.

A Lebanese adaptation portfolio should include long-term weather and phenology monitoring; water budgeting; deficit irrigation trials; soil moisture conservation; evaluation of rootstocks; canopy and shade management; adjustment of harvest timing; screening of local genotypes and clones; and spatial analysis of future suitability. High-altitude vineyards may provide thermal buffering, but elevation is not a universal solution because frost, water access, soil depth, erosion and infrastructure also matter.

Climate adaptation should also be linked to biodiversity conservation. Local genotypes maintained for centuries across diverse Lebanese environments may contain useful traits, but their adaptive value cannot be assumed from origin alone. Conservation, genetic characterization and agronomic stress testing should, therefore, proceed together. Earlier Lebanese sector analysis identified structural and institutional weaknesses requiring coordinated sector development [35].

Water availability is likely to become one of the defining constraints on the future geography of Lebanese viticulture. The Mediterranean basin is a climate change hotspot in which increasing temperatures, greater evaporative demand and altered precipitation regimes interact with already intense competition for water. Southern European experience shows that vineyard adaptation cannot be reduced to simply supplying more irrigation. Costa et al. [13] emphasize coordinated use of deficit irrigation, canopy regulation, soil management, plant material and improved water-use efficiency. Schultz [36], Jones and Webb [37], and Holland and Smit [38] similarly frame climate adaptation as a combination of physiological, technical and institutional responses. For Lebanon, where vineyards range from relatively dry interior environments to cooler high-elevation sites, the priority should be to determine crop water requirements and vine responses under specific combinations of cultivar, rootstock, soil depth and elevation rather than adopting generalized irrigation prescriptions.

Soil management is equally important because soil is both a production resource and a component of terroir. Intensive tillage, bare soil and poorly managed slopes can accelerate erosion and organic-matter loss, while excessive fertilizer use can increase environmental burdens without necessarily improving grape quality. Mediterranean viticulture increasingly uses temporary or permanent cover crops, mulches, composts and reduced tillage to improve infiltration, biological activity and erosion control. These practices must, nevertheless, be adapted to water-limited environments because unmanaged cover vegetation may compete with vines during dry periods. The appropriate objective for Lebanese vineyards is, therefore, not universal greening, but site-specific soil stewardship based on slope, rainfall, irrigation access, vine vigor and erosion risk. Biasi et al. [39] demonstrate more broadly that viticulture can contribute to maintaining vulnerable Mediterranean landscapes when cropping systems are managed as part of land conservation strategies.

Biodiversity provides another bridge between vineyard sustainability and landscape quality. Vineyard monocultures can be biologically simplified, but vineyards embedded within heterogeneous mosaics of field margins, orchards, woodland, terraces and semi-natural vegetation can support ecological functions. The sustainability literature cited by Galletto and Barisan [40] stresses links between vineyard practices, neighboring habitats and ecosystem services. Lubell et al. [41] further show that adoption of sustainable agricultural practices is influenced by perceived benefits, costs, cooperation and innovation networks. In Lebanon, this implies that biodiversity measures should be designed at both parcel and landscape scales: maintaining non-crop vegetation where compatible with fire and water management, reducing unnecessary insecticide use, protecting beneficial arthropods, and retaining landscape elements that contribute to ecological connectivity.

Integrated pest and disease management deserves explicit inclusion in a national wine sustainability framework. Grapevines are exposed to fungal diseases, arthropod pests and vector-borne pathogens, and climate change may alter both pest pressure and the timing of interventions. A sustainability strategy should prioritize monitoring, forecasting, threshold-based decisions, biological and cultural controls where effective, and pesticide selection based on efficacy and non-target effects. Such an approach is consistent with the broader OIV concept of sustainable vitiviniculture, which considers environmental, social and economic viability across production and processing rather than defining sustainability through a single input or certification label [42].

The agroecological perspective is also relevant to the preservation of old vines and marginal vineyards. Recent Lebanese genetic surveys recovered substantial diversity from old or abandoned vines, home gardens and small family plots [4,19]. These landscapes function as informal reservoirs of genetic resources. Their disappearance through urbanization, abandonment or replacement by a narrow set of commercial cultivars would, therefore,

represent both cultural and biological loss. Conservation policy should recognize farmers who maintain rare material, create incentives for documented on-farm conservation, and connect growers with national germplasm collections and nurseries capable of producing true-to-type, healthy planting material.

7.1. Climate Hazards and Vineyard-Level Response Pathways

Lebanese observations should be interpreted at three distinct evidentiary scales: national climate and water assessments, measurements from individual Lebanese vineyards, and mechanistic evidence transferred from Mediterranean wine regions. National communications and adaptation planning documents identify heat, precipitation variability and water scarcity as relevant agricultural risks, but do not establish vineyard-specific changes in harvest date, wine quality or cultivar suitability. The two-site Lebanese 'Cabernet Sauvignon' analysis by Ghantous et al. [8] provides more directly relevant evidence of weather-associated variation in yield and berry traits; however, its cultivar and site coverage precludes a national causal generalization. Mediterranean syntheses [13–15,36–38] support plausible responses—earlier phenological development under warming, increased atmospheric water demand, and site-dependent changes in sugar–acid balance—but the magnitude of each response in Lebanon requires multi-vintage verification.

An evidence-based adaptation protocol would pair automatic weather records (daily minimum and maximum temperatures, rainfall, humidity and reference evapotranspiration) with vine observations (budburst, flowering, veraison, harvest, midday stem water potential where feasible, yield and must sugar, acidity and pH). Trials should be stratified by cultivar, rootstock, elevation, soil depth and irrigation status. Heat-event thresholds and growing-degree-day indices should be calculated from a stated base temperature and observation period rather than inferred from regional altitude alone. This would allow growers to evaluate canopy shading, pruning date, harvest timing and irrigation adjustments against measured berry composition and economic outcomes, not presumed climatic benefits.

7.2. Water and Soil Conservation: Conditional Interventions

Water management should begin with a seasonal water balance distinguishing rainfall, effective soil-water storage and applied irrigation. For each trial parcel, metered irrigation ($m^3\ ha^{-1}$), yield ($t\ ha^{-1}$), and, where available, vine water status and soil moisture should be recorded. Regulated deficit irrigation and partial-root-zone drying are candidate techniques from Mediterranean research [13], not nationally validated prescriptions for Lebanese cultivars. Their evaluation should test fruit composition, yield stability, salinity risk and competing water demands across wet and dry vintages. For unirrigated vineyards, soil-water conservation and canopy adjustment may be more relevant than improving irrigation efficiency. A water-use indicator alone is insufficient if the water source, extraction season and basin-level scarcity are unknown.

Soil management interventions likewise involve trade-offs. On steep or erosion-prone sites, contour-aligned groundcover, vegetated buffer strips and reduced soil disturbance may reduce runoff and sediment loss; on shallow, water-limited soils, unmanaged cover crops may intensify competition for water. Lebanese field trials should, therefore, compare bare inter-rows, seasonal cover and managed vegetation using soil organic carbon, infiltration, surface cover, erosion proxies, soil moisture and vine performance, with consistent sampling depth and season. These options derive principally from Mediterranean agronomic experience [13,39] and should be framed as testable practices rather than demonstrated Lebanese outcomes.

7.3. Lebanese Applications, Verification and Implementation Limits

Harb et al. [7] provide a Lebanon-specific life-cycle assessment case study that demonstrates how vineyard inputs, winery operations and packaging can be assessed within one analytical framework. It is an important local example, but its results cannot be assumed representative of wineries with different bottle weights, electricity sources, irrigation regimes or export destinations. Similarly, reported sustainability initiatives in Lebanese wineries [43] may indicate organizational interest, but their environmental effectiveness requires audited inventories and longitudinal performance data. Examples suitable for future Lebanese pilots include electricity metering by processing stage, quantification of wash-water use and treatment, weighing of glass per 750 mL bottle, and separate recording of grape pomace, stems and lees. These are proposed monitoring activities, not reported national achievements.

Implementation should be proportionate to producer capacity. A first tier could require annual records of vineyard area and grape yield, irrigation volumes where relevant, pesticide applications, electricity and fuel, winery water use, and bottle mass. A second tier could add soil-carbon sampling, biodiversity transects, wastewater quality tests and a cradle-to-gate life-cycle inventory. For meaningful comparison, every indicator requires a baseline year, consistent denominator (per hectare, ton of grapes or liter of wine), system boundary, quality control procedure and uncertainty statement. No universal numerical reduction targets are proposed because comparable Lebanese baselines have not yet been established.

Vineyard biodiversity should be evaluated through repeatable observations rather than the presence of a particular landscape feature alone. Suggested measurements include mapped semi-natural habitat area, standardized transects or traps for selected beneficial arthropod groups, and pesticide applications recorded by product, active ingredient, dose, target and date. A treatment frequency index may facilitate comparisons but does not itself quantify ecotoxicity; risk-weighted assessments and monitoring of non-target organisms would be stronger where resources permit. Integrated pest management should combine surveillance of locally occurring grapevine pests and diseases, phenology-based forecasting, cultural measures and documented treatment decisions. The current manuscript does not contain a representative Lebanese multi-region dataset demonstrating reduced pesticide impacts or increased natural enemy abundance; these remain priorities for prospective studies.

Conservation of old vines should be treated as a genetic resource intervention with a measurable outcome. The molecular surveys [4,19] document diversity in sampled material, including old and underdocumented vines, but cannot establish the number of threatened cultivars nationwide. A practical program would georeference accessions, confirm identity by standardized genotyping, record vine health and propagation success, and link on-farm conservation with ex situ repositories. Screening this material for drought tolerance or disease resistance must follow replicated phenotyping; historical survival alone is not proof of adaptation.

Connection to contemporary winemaking. The scientific relevance of cooked-wine fermentations is methodological rather than evidence that such techniques should be transferred directly to dry wine production. High-sugar fermentation studies can identify stress-tolerant microbial phenotypes and generate hypotheses for controlled starter-strain screening, fermentation completion, and product safety. Any application to contemporary low-intervention or commercial wines requires separate trials using representative musts, appropriate controls, and chemical and sensory quality endpoints [34].

8. Fermentation Microbiology and Evidence for Biological Terroir

Fermentation microbiology represents an emerging dimension of Lebanese vitiviniculture research, although its relationship with terroir requires careful interpretation. Feghali et al. [6] characterized 202 *Saccharomyces cerevisiae* isolates associated with spontaneous 'Merwah' fermentations sampled over two years at a traditional high-altitude winery in Mount Lebanon. The reported genetic and phenotypic diversity provides evidence of heterogeneous fermentation-associated yeast populations and identifies candidate strains for further technological evaluation. However, the study's site-specific design does not establish whether the observed population structure is stable across wineries, vintages, grape origins, or cellar environments. Nor does yeast diversity alone demonstrate a consistent sensory contribution attributable to geographical origin.

In a distinct traditional product system, Bechara et al. [34] examined spontaneous fermentations of Lebanese cooked wines under elevated sugar concentrations. This work contributes to understanding microbial succession under processing-induced stress, but its findings should not be extrapolated directly to conventional grape-wine fermentations. The composition and dynamics of fermentation microbiota can be shaped by grape chemistry, processing, equipment, inoculation history, environmental conditions, and cellar management; consequently, the geographic provenance of an isolate should not be equated with proof of microbial terroir.

Testing a reproducible Lebanese microbial-terroir hypothesis would require replicated sampling across grape-growing regions, wineries, fermentation vessels and successive vintages, combined with strain-resolved microbiological characterization, controlled fermentations, chemical profiling, and blinded sensory evaluation. Where possible, cross-inoculation experiments should separate yeast strain effects from grape matrix and winery effects. Until such evidence becomes available, native or locally recovered yeasts are best described as promising biological resources for strain selection and future research, rather than established determinants of regional wine identity.

Technological Validation of Local Fermentation Resources

The 'Merwah' isolate survey characterized 202 yeast isolates from one winery over two vintages and selected candidate strains for further testing [6]. A subsequent pilot-scale inoculation study offers an important process validation: of three indigenous strains tested, only strain M.4.17 successfully dominated the fermentation, while chemical and sensory analyses supported its suitability for the studied winery and vintage [33]. These findings demonstrate a pathway from strain isolation to pilot-scale evaluation, not a reproducible region-wide microbial signature. Broader claims of microbial terroir would require matched vineyard and winery sampling, repeated vintages, controls for cellar effects, and blinded sensory comparisons [33].

9. Environmental Sustainability and Measurable Indicators

The environmental performance of vitiviniculture should be evaluated across interconnected vineyard and winery operations rather than inferred from the adoption of individual practices. In Lebanon, the available life-cycle assessment evidence provides a starting point for identifying potential environmental hotspots along the wine production chain [retain and verify existing Lebanese LCA citation]. However, the magnitude and ranking of impacts depend on the functional unit, system boundaries, production scale, packaging configuration, energy sources and transport assumptions. Consequently, findings from the assessed production systems should not be generalized to all Lebanese wineries without further comparative studies.

At the vineyard level, water availability, soil conservation, groundcover management, fertilizer and pesticide inputs, and the maintenance of semi-natural habitats are interrelated management dimensions. Their effects should be assessed in terms of measured water use, soil properties, erosion risk, crop performance, biodiversity and input intensity, rather than treated as universally beneficial interventions. In water-limited environments, for example, cover crops may improve soil protection but can also compete with grapevines for moisture; site-specific testing is, therefore, required before recommending their widespread adoption in Lebanon.

At the winery level, energy and water consumption, wastewater treatment, organic by-products, packaging materials and transport contribute to environmental performance. Comparisons should use consistent functional units and transparent boundaries and should distinguish vineyard operations from downstream packaging and distribution. Claims about the benefits of circularity, alternative packaging or renewable energy should be supported by measured inventories or clearly identified as plausible options requiring local assessment.

Environmental sustainability in Lebanese vitiviniculture should be assessed through measured outcomes rather than inferred from the adoption of particular practices or the possession of certification. The Lebanese life-cycle assessment by Harb et al. [7] demonstrates the relevance of a production-chain perspective; however, the findings of an individual assessment should not be generalized to all Lebanese wineries without accounting for differences in vineyard conditions, electricity sources, packaging, production volumes and system boundaries. A harmonized national monitoring framework would permit comparisons across participating vineyards and wineries while making these differences transparent.

We propose a tiered indicator system covering water withdrawals and use efficiency; energy consumption and greenhouse gas emissions; pesticide use and associated risk; soil cover, erosion and soil organic carbon; biodiversity-supporting habitat; and winery wastewater, packaging and residual material flows (Table 6). Indicators should be reported with defined units, spatial and temporal boundaries, data provenance, and, where relevant, production-normalized and area-normalized values. For example, irrigation volumes per hectare should be interpreted alongside irrigation volumes per kilogram of harvested grapes because yield variability can alter the apparent efficiency of a practice. Similarly, greenhouse gas comparisons require consistent life-cycle boundaries and emission factors.

Certification and sustainability labels may provide organizational incentives, audit procedures and traceability, but certification status is not itself a quantitative measure of environmental benefit. Claims of improved performance require baseline measurements, repeated monitoring, transparent calculation methods and evidence of change. In the absence of representative Lebanese baseline datasets, the indicators below are proposed research and management priorities, not verified national performance benchmarks. Pilot implementation should begin across contrasting regions, elevations, irrigation regimes and winery scales before any national targets are established.

Quantitative sustainability reporting should begin with auditable measurement rather than assumed target values. Recommended calculation conventions include irrigation water applied (m^3/ha/season and L/kg harvested grapes), total winery water intake (L/L finished wine, with cleaning and processing boundaries stated), energy (kWh/L finished wine), bottle and packaging mass (g per 750 mL equivalent), and greenhouse gas emissions (kg CO_2-equivalent per 750 mL bottle, with stated life-cycle stages). Soil organic carbon should be reported as concentration (g/kg or %) together with sampling depth and, where feasible, bulk-density-adjusted stocks (Mg C/ha). Water productivity (kg grapes/m^3 irrigation water) must not be confused with total crop evapotranspiration productivity. These are proposed reporting units, not numerical targets or measured Lebanese averages.

Table 6. Proposed core indicators for sustainability monitoring in Lebanese vitiviniculture (not national measurements).

Domain	Core Indicator (Unit)	Measurement and Interpretation	Key Caveat
Water	Irrigation applied (m^3/ha/season); m^3/t grapes	Metered withdrawals, irrigation logs, and harvest mass; report rainfall and irrigation status	Water-use efficiency depends on yield, climate and water source
Energy	Electricity and fuel (kWh/hL wine); kWh/ha	Utility bills, generator fuel and winery/vineyard allocation	Grid and generator energy require separate accounting
Climate impact	GHG emissions (kg CO_2-eq/750 mL bottle or L wine)	Life-cycle inventory with stated boundaries and emission factors	Do not compare different system boundaries as equivalent
Plant protection	Active ingredient (kg/ha/year) plus risk-based pesticide indicator	Spray records, active ingredients, treatment frequency and hazard/risk method	Mass alone does not reflect toxicity or exposure
Soil	Ground cover (%); soil organic carbon (g/kg or t C/ha); erosion observations	Permanent plots, seasonal cover assessment and repeated soil sampling	Soil carbon changes slowly; methods and depth must match
Biodiversity	Semi-natural habitat share (%); standardized indicator taxa	Mapped habitat and repeatable biodiversity sampling protocols	Habitat extent is not equivalent to demonstrated species recovery
Winery water and effluent	Water use (L/L wine); effluent volume and quality	Meters, effluent flow, COD/BOD and treatment records where feasible	Seasonal peaks and treatment performance should be recorded
Materials and packaging	Bottle mass (g); packaging and by-products (kg/hL)	Packaging inventory, waste and recovery records	Recycling rates do not by themselves quantify life-cycle benefit

A defensible national benchmark would require a multi-winery baseline with consistent functional units, production volumes, packaging mixes, electricity supply, wastewater accounting and climate/site strata. Percent contributions of glass manufacture to carbon footprint or fixed soil organic matter thresholds cannot be transferred from other countries without matching system boundaries and local soil constraints. The Lebanese life-cycle study [7] should be consulted for its precise numerical inventory and impact allocation before quoting percentages. Until then, comparisons should emphasize within-site change, uncertainty intervals and independent data checks rather than unsupported cross-winery rankings.

10. Evidence-Based Research Priorities and Implementation

The available literature supports a proposed framework comprising six interconnected research and implementation pillars (Table 7). These pillars are intended to organize the available evidence, expose its limitations, and identify testable priorities; they should not be interpreted as interventions already validated at the national scale. Climate adaptation and coordinated research governance are cross-cutting considerations. The framework places grapevine and vineyard characteristics at its center, while commercial differ-

entiation and territorial value are considered potential downstream outcomes requiring independent assessment.

Table 7. Six proposed research and implementation pillars: evidence, gaps, actions, indicators and actors.

	Pillar	Available Evidence	Principal Gap	Proposed Actions	Illustrative Indicators	Potential Lead Actors
1.	Grapevine genetic resources	Lebanese molecular and ampelographic surveys document diversity; coverage and identification remain incomplete	Representative conservation and cultivar/clone performance data	Verified accession registry; ex situ/on-farm conservation; replicated cultivar trials	Genotyped accessions; conserved unique profiles; trial sites; evaluated cultivars	Universities, LARI, growers, and nurseries
2.	Terroir and vineyard performance	Lebanese site-specific studies link management and weather to vineyard performance	Multi-region soil, phenology, yield and berry composition series	Harmonized terroir mapping and multi-site observations	Mapped hectares; site-years; standardized phenology and berry quality records	Universities, LARI, wineries, and growers
3.	Climate and water resilience	Limited Lebanese vineyard weather evidence; Mediterranean comparators provide context	Locally validated water balance, irrigation and heat/drought responses	Climate–vineyard observatories and replicated adaptation trials	Weather stations; water-use records; vine water status; yield/quality stability	LARI, universities, water authorities, and growers
4.	Vineyard sustainability	Lebanese wine life-cycle case evidence and broader Mediterranean agroecological studies	National baselines for soil, inputs, biodiversity and environmental impacts	Field monitoring, integrated pest management, soil conservation and harmonized LCA boundaries	Soil organic carbon; erosion; pesticide use; water/energy intensity; LCA metrics	Growers, wineries, universities, and extension services
5.	Fermentation biology and wine quality	Lebanese studies document diverse native yeasts and fermentation potential	Cross-vintage, cross-site technological and sensory reproducibility	Replicated fermentations, strain characterization and sensory validation	Validated strains; replicated vintages/sites; fermentation outcomes; sensory repeatability	Universities, wineries, and microbiology laboratories
6.	Knowledge integration and imple-mentation	Fragmented evidence and limited comparable longitudinal datasets	Shared protocols, data stewardship, coordinated trials and extension	Common descriptors, open research inventory, coordinated monitoring and training	Institutions participating; datasets standardized; protocols adopted; annual outputs	Universities, LARI, ministries, and grower/winery associations

The evidence is uneven across pillars. Lebanese molecular surveys demonstrate the presence of substantial grapevine genetic diversity, but field-based characterization of performance remains limited. Vineyard–weather relationships have been investigated at restricted sites and cultivars; extrapolation to other Lebanese growing regions, therefore, requires caution. Studies of indigenous fermentation microbiota document biological diversity, but reproducible sensory signatures across sites and vintages have not been established. Similarly, available environmental assessments identify potential improvement opportunities within particular system boundaries, not a verified national sustainability baseline. The actions and indicators in Table 6 respond directly to these limitations.

Institutional responsibility and financing should be assigned by deliverable rather than presumed from institutional mandates. As a feasible voluntary pilot, participating wineries and growers could establish a consortium to fund standardized parcel registration and annual reporting; university laboratories and LARI could provide scientific protocols, independent sampling and quality assurance, subject to written agreements and available capacity. The Ministry of Agriculture and any competent wine-sector body should be invited to review regulatory compatibility and eventual adoption, without assuming that a functioning national registry already exists. A steering committee with grower, winery, research and public-sector representation could publish an annual progress report and conflict-of-interest policy.

A staged financing approach could combine in-kind vineyard access, participating-winery contributions and competitively awarded national or international research grants. The initial 12-month pilot would establish governance, consent procedures and a minimal dataset; years 2–3 would prioritize replicated cultivar–site trials and water/soil monitoring; years 4–5 could support external validation, voluntary traceability and a public regional atlas. These periods are proposed planning horizons, not funded commitments. Each phase should have a stop/go decision based on data completeness, independent verification and producer participation.

The six pillars in Table 7 constitute a proposed research agenda rather than a list of established interventions. Implementation should begin with a harmonized vineyard and winery baseline (cultivar identity, planting area, elevation, management, output and destination), followed by multi-site and multi-vintage trials linking genotype, vine performance, water status, berry chemistry and fermentation outcomes. Comparable life-cycle boundaries and the indicators in Table 3 should be adopted in parallel. These shared protocols would allow evidence from individual institutions and producers to accumulate, while protecting commercially sensitive records.

A phased implementation pathway is advisable. In the near term, participating universities, growers and wineries could agree on data definitions, reference vineyards, sampling methods and transparent quality controls. In the medium term, replicated cultivar–site and irrigation trials, climate–phenology observatories, fermentation validation and environmental benchmarking could test the most actionable hypotheses. In the longer term, validated results could inform planting decisions, traceability, geographical origin initiatives and extension services. Responsibilities and indicators are specified in Table 4; no national-scale effectiveness is claimed for this proposed sequence.

Socioeconomic and landscape work should accompany, rather than substitute for, these biophysical measurements. Repeated consumer surveys, including generational and involvement-based segmentation [27,28], can evaluate changes in purchasing behavior and the potential market value of verified origin or sustainability claims. Spatial monitoring of vineyard conversion, land abandonment, wildfire exposure and tourism infrastructure can support territorial planning. These downstream outcomes require separate empirical

assessment; neither genetic uniqueness nor archeological heritage is sufficient evidence of commercial success.

Wine tourism should be evaluated as a complementary territorial activity rather than assumed to generate net economic or environmental benefits. A feasible voluntary governance model could involve a participating-winery association, municipal clusters and tourism operators coordinating route information, visitor safety, landscape safeguards and shared reporting, with the Ministry of Tourism and other public bodies consulted where appropriate. Potential financing sources include member contributions, fee-based services and competitively awarded project grants; none is represented here as an existing commitment. Proposed indicators include visitor counts, tourism-related winery receipts, seasonal employment, local procurement, visitor water and energy demand, and traffic or land-use pressures. These metrics should be stratified by winery size and region.

Lebanon-specific risks to wine tourism include geopolitical instability, disruptions to transport and electricity, and uneven access to visitor services. Accordingly, any route or territorial-branding proposal should include operational continuity, emergency communication and infrastructure needs in its feasibility assessment. Consumer segmentation studies [27,28] are relevant for formulating hypotheses about visitor and buyer groups, but willingness to pay for sustainability or origin claims in target export markets remains an empirical gap rather than an established price premium.

11. Conclusions

Lebanese vitiviniculture is at a strategic crossroads. Its ancient heritage remains a powerful cultural asset, but heritage alone cannot secure future competitiveness. The strongest new scientific evidence comes from the rediscovery of grapevine genetic diversity, the characterization of indigenous fermentation microbiota, environmental life-cycle assessment and the emerging documentation of climate sensitivity. Together, these studies shift the discussion from promotional narratives toward measurable biological, environmental and territorial distinctiveness.

The sector's relatively limited scale may offer opportunities for quality-oriented differentiation, but it also creates exposure to production costs, climatic variability and export market constraints. Potential advantages associated with grapevine diversity, contrasting elevations, heritage and gastronomy require testing through agronomic, oenological and market evidence rather than being assumed as established competitive strengths.

The central conclusion is, therefore, methodological and practical: Lebanese vitiviniculture needs coordinated, reproducible measurements that connect germplasm, terroir, vineyard performance, wine quality, environmental impacts and economic outcomes. The consolidated six-pillar agenda in Section 10 provides a basis for such work; its proposed interventions and indicators should be evaluated before claims of nationwide effectiveness are made.

The next phase of Lebanese wine development should, consequently, prioritize knowledge infrastructure as much as marketing, including national vineyard data, germplasm conservation, multi-site trials, climate observatories, sustainability indicators, traceability and territorial planning. With these foundations, individual winery innovation and collective regional branding can reinforce rather than compete with one another. This integrated pathway offers the most credible basis for a resilient, distinctive and internationally recognizable Lebanese wine sector.

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