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Stevia Sweetened Golden Berry and Strawberry Wine as a Low Sugar Option with Antioxidant Activity and Good Sensory Acceptance for Diabetes Conscious Consumers

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Abstract

Conventional fruit wines typically retain residual sugars that pose glycaemic risks for people living with diabetes, and co-fermenting underutilised fruits such as golden berry (*Physalis peruviana*) and strawberry (*Fragaria × ananassa*) to reduce sugar remains poorly documented. This study developed and evaluated a low-sugar, diabetic-friendly wine produced by co-fermenting golden berry and strawberry juices and sweetening the fermented product with stevia. Golden berry and strawberry juices were blended at three ratios—Blend A (40:60), Blend B (50:50) and Blend C (60:40, golden berry: strawberry)—pasteurised, inoculated with *Saccharomyces cerevisiae*, and fermented to dryness over 21 days before stabilisation with potassium metabisulfite and post-fermentation sweetening with stevia (4–6 g/L). Final pH, total soluble solids (°Brix), alcohol content, titratable acidity, antioxidant activity, and sensory acceptability (15 untrained panelists, 5-point hedonic scale) were assessed. Final pH values were 3.52 ± 0.02, 3.30 ± 0.02 and 3.29 ± 0.02 for Blends A, B and C, respectively, with corresponding °Brix of 0.50 ± 0.07, 0.30 ± 0.06 and 0.20 ± 0.05. Blend B (equal-ratio) recorded 10.05 ± 0.07% ABV and titratable acidity of 6.1 ± 0.07 g/L, and received the highest sensory scores for appearance (4.6 ± 0.3), taste (4.4 ± 0.3), flavour (4.5 ± 0.2), aroma (4.3 ± 0.3) and overall acceptability (4.6 ± 0.3). Antioxidant activity increased with golden berry proportion (Blend A 0.82, Blend B 0.95, Blend C 1.02 absorbance units). The equal-ratio formulation (Blend B) was the most acceptable prototype, combining a balanced acid–sweetness profile, moderate alcohol content, and antioxidant capacity. These findings indicate that stevia-sweetened golden berry–strawberry co-fermentation can yield a visually appealing, low-residual-sugar wine with functional potential for diabetes-conscious consumers, although the product should be regarded as an experimental prototype rather than a clinically validated diabetic beverage.

1. Introduction

Fruit wines are fermented alcoholic beverages produced from fruits other than grapes, using processing steps broadly similar to grape-wine production: juice extraction, pasteurisation, yeast inoculation, fermentation, clarification, stabilisation and bottling [1, 2]. They are conventionally named after their source fruit, such as elderberry or cherry wine, or increasingly produced as co-fermented blends of two or more fruits to achieve a more complex sensory profile. Wine in the broadest sense has accompanied human civilisation for more than 8,000 years, evolving from an artisanal household practice into a technically sophisticated, commercially important sector of the global food and beverage trade [3, 4]. In sub-Saharan Africa, and in Rwanda specifically, fruit-based fermented beverages occupy an important cultural and economic place, both as components of social and ceremonial life and as small-scale, income-generating value-addition activities for smallholder farmers and agro-processors who would otherwise face substantial postharvest losses.

Golden berry (*Physalis peruviana* L.), also known as cape gooseberry, is an acidic, aromatic fruit of the Solanaceae family that has attracted growing scientific and commercial interest for its distinctive nutritional and phytochemical profile [5]. It is a recognised source of vitamin C, provitamin A carotenoids, physalins, polyphenols and dietary fibre, and its pulp carries relatively high titratable acidity from citric

and malic acids alongside a moderate, fermentable sugar content. These attributes make golden berry an attractive fermentation substrate, since its natural acidity supports microbial stability while its phytochemical load offers potential antioxidant benefits relevant to consumers managing chronic conditions such as diabetes. Despite this potential, golden berry remains among Africa's underutilised fruit crops, with little published work examining its behaviour during alcoholic fermentation, alone or in combination with other fruits.

Strawberry (*Fragaria × ananassa*), by contrast, is among the most widely cultivated soft fruits worldwide, valued for its red colour, aroma, and balanced sweetness-acidity profile. It contributes anthocyanins, ellagic acid and other phenolics, vitamin C, and readily fermentable sugars (glucose, fructose, sucrose), supporting rapid, complete fermentation. Strawberry wines produced without compositional modification, however, tend to retain high residual sugar unless fermented to dryness. Combining golden berry and strawberry before fermentation was therefore hypothesised to yield a beverage with complementary colour, acidity, aroma and flavour that neither fruit achieves alone [6, 7].

Co-fermentation, the simultaneous fermentation of a blended juice from two or more fruits, differs from blending finished single-fruit wines after fermentation in that yeast is exposed throughout primary metabolism to the combined sugar, acid and phenolic matrix of both fruits, influencing fermentation kinetics, ester formation, and pigment retention in ways that post-fermentation blending cannot replicate. This approach remains comparatively underexplored for golden berry and strawberry despite the apparent complementarity of their profiles: golden berry supplying acidity, phytochemicals and moderate sugar, strawberry supplying colour, aroma-active volatiles and a higher fermentable-sugar load. Systematic characterisation of blending-ratio effects, rather than reliance on a single fixed formulation, is therefore necessary to identify a composition suited to stevia sweetening and reduced residual sugar. Yeast strain selection is a further, established determinant of flavour and aromatic complexity in fruit-wine fermentation, since different *Saccharomyces* and non-*Saccharomyces* strains vary in ester and higher-alcohol production and in tolerance to the acid and phenolic conditions typical of non-grape musts [8, 9]. A single commercial *S. cerevisiae* strain was therefore retained across all three blending ratios in the present study, so that differences in fermentation outcome and sensory quality could be attributed to fruit composition rather than to yeast variability, while strain optimisation remains an avenue for future work [10].

Conventional fruit wines commonly retain residual sugars, either because fermentation is halted before dryness to preserve sweetness, or because sugar is added to correct low natural sugar content; such residual sugar poses recognised glycaemic risks for people living with diabetes [11, 12]. Reformulation using non-nutritive sweeteners has been proposed to reconcile sensory sweetness with reduced glycaemic impact, but the effects of specific sweeteners, stevia in particular, on the stability, sensory quality and acceptance of fermented fruit beverages remain comparatively under-explored, especially in contexts such as Rwanda, where fruit wines and banana beer already occupy an established place in everyday consumption [13]. Stevia (*Stevia rebaudiana* Bertoni), whose principal sweet constituents are the steviol glycosides, is widely recognised as safe, negligibly caloric, and minimally glycaemic, making it

a logical candidate sweetener for diabetic-friendly beverages. Because stevia is not fermentable by *Saccharomyces cerevisiae*, it was added after fermentation was complete in the present study, avoiding any confounding effect on yeast metabolism or alcohol yield; its distinctive, sometimes lingering aftertaste at higher concentrations motivated the inclusion of formal sensory evaluation alongside physicochemical analysis.

Diabetes prevalence continues to rise worldwide, including in sub-Saharan Africa and Rwanda specifically, as dietary transition and urbanisation contribute to a growing burden of diet-related non-communicable disease, even as traditional alcoholic beverages remain widely consumed [14, 15]. This study therefore addressed a dual gap: the lack of evidence-based, low-sugar fruit-wine formulations that meet the dietary needs of diabetes-prone consumers without compromising sensory quality and cultural acceptability [16], and the lack of systematic characterisation of golden berry-strawberry blends specifically formulated and evaluated for this purpose, rather than treated as a single-ratio novelty product. Golden berry contributes fermentable sugar and acidity sufficient to support stable dry fermentation without external sugar, while strawberry enhances flavour, aroma and anthocyanin-associated antioxidant content that may help offset the oxidative stress associated with diabetes and its complications [17, 18]. Combining antioxidant assessment with structured sensory testing strengthens both the scientific rigour and market relevance of formulations developed along these lines [19, 20].

Addressing these gaps is important for Rwanda's fruit and beverage sector, where value-addition to underutilised local fruits such as golden berry could simultaneously support smallholder income, reduce postharvest losses, and expand health-oriented beverage options. This study therefore aimed to produce and characterise a low-sugar, diabetic-friendly wine, stevia-sweetened following dry co-fermentation of golden berry and strawberry juices at three blending ratios, by (i) determining the physicochemical properties, namely pH, alcohol content, total soluble solids, titratable acidity and antioxidant activity, of the resulting wines, and (ii) evaluating their sensory acceptability across appearance, taste, flavour, aroma and overall acceptability, in order to identify the blending ratio best suited to further development as a functional, diabetes-conscious beverage. Because fruit wine is, by definition, an alcoholic beverage, any health-oriented framing of the product must be considered alongside the established metabolic effects of alcohol itself, a point discussed further in Section 3.3; within this bounded sense, a stevia-sweetened, dry co-fermented golden berry-strawberry wine represents a legitimate, if modest, contribution to the broader landscape of reformulated, lower-sugar alcoholic beverages.

Taken together, the introduction above establishes three interlocking justifications for the present study: a compositional justification, resting on the complementary acid, sugar, colour and phytochemical profiles of golden berry and strawberry; a technical justification, resting on the comparatively unexplored dry co-fermentation and post-fermentation stevia-sweetening approach used to limit residual sugar without external additive sugar; and a public-health justification, resting on the growing regional and global burden of diabetes and the corresponding need for culturally appropriate, lower-sugar alternatives within categories of beverage, such as fruit wine, that are already widely consumed. The remainder of this manuscript reports the physicochemical and sensory characterisation of the three blending ratios

tested against these three justifications in turn, before discussing the implications of the findings for further product development and for the broader value chain within which this formulation work is situated.

2. Materials and Methods

2.1 Materials and sample collection

Fresh golden berries (2 kg) and strawberries (2 kg) were purchased from local markets in Musanze District, Northern Province, Rwanda. Dried *Saccharomyces cerevisiae* wine yeast (10 g) was obtained from a supplier in Kigali, and stevia extract was purchased from a supermarket in Musanze District. Raw materials were transported in clean baskets and held at room temperature prior to processing.

2.2 Juice preparation and blending

Golden berries were hulled, washed with potable water, chopped, and blended to extract juice; the juice was pasteurised at 70–80°C for 15 min, cooled to 35°C, and stored in sterilised containers. Strawberries were processed identically: washed, chopped, blended, and pasteurised at 70–80°C for 15 min before cooling and sterile storage [21, 22].

Three golden berry: strawberry juice blends were prepared by volume — Blend A (40:60), Blend B (50:50), and Blend C (60:40)—mixed thoroughly in a clean saucepan with a sterilised stirrer to ensure homogeneity and prevent contamination. Each blend was pasteurised for 15 min at 75°C, cooled to room temperature, and transferred to separate fermentation vessels under controlled conditions [23, 24].

2.3 Dry fermentation, stabilisation and stevia sweetening

Fermentation followed the dry-fermentation principle of the International Organisation of Vine and Wine (OIV) [22], in which no external sugar is added and fermentation relies solely on the natural sugars present in the fruit. Pasteurised blends were inoculated with 0.5 g/L of *Saccharomyces cerevisiae* wine yeast and fermented for 21 days at room temperature, with °Brix monitored daily using a refractometer to track sugar depletion until dryness was reached (residual sugar < 1 g/L).

On completion of fermentation, wines were stabilised with potassium metabisulfite to prevent microbial spoilage, and stevia extract was added at 4–6 g/L to each blend to restore sweetness without increasing glycaemic load, yielding a balanced, safe and palatable low-sugar product.

2.4 Physicochemical analyses

pH was measured with a pH electrode calibrated sequentially against pH 4.00 and 7.00 buffer solutions, rinsing and drying the electrode between calibration points; the electrode was then immersed in 40 mL of each wine sample and the stabilised reading recorded.

Alcohol content was determined by distillation: 100 mL of each wine sample was distilled, the distillate made up to volume with distilled water, and alcohol content read using an alcohol meter [25, 26].

Total soluble solids (°Brix) were measured with a refractometer calibrated against distilled water; a few drops of sample were placed on the prism, and readings were taken at the light–dark boundary through the eyepiece, with the prism cleaned and dried between samples.

Titratable acidity (TA) was determined according to test method RS EAS 104 (Rwanda Standards Board): 10 mL of sample was diluted with 100 mL distilled water, 2–3 drops of phenolphthalein indicator were added, and the mixture was titrated with 0.1 N NaOH to a faint pink end-point persisting for 30 s, with titrations performed in triplicate. Titratable acidity was calculated as:

$$TA = (V_B \times N_B \times 0.060 \times 1000) / V_S$$

where V_B is the volume of NaOH used (mL), N_B is the normality of NaOH, and V_S is the sample volume (mL).

Antioxidant activity was assessed by the ferric-reducing method: 2.5 mL of wine sample was mixed with 2.5 mL of 0.2 M phosphate buffer (pH 6.6) and 2.5 mL of 1% potassium ferricyanide solution, incubated at 50°C for 20 min, cooled in iced water, and centrifuged; 2.5 mL of supernatant was combined with 2.5 mL distilled water and 0.5 mL of 0.1% ferric chloride solution, and absorbance was read at 700 nm on a UV–visible spectrophotometer [27].

2.5 Sensory evaluation

Sensory acceptability was assessed using the hedonic rating method, commonly applied in food and beverage research to determine consumer liking [28]. A panel of 15 untrained panelists (male and female, aged 18–45 years) evaluated appearance, taste, flavour, aroma and overall acceptability on a 5-point hedonic scale (1 = dislike extremely, 5 = like extremely). Coded samples were served in clean transparent glassware under normal daylight, and water and plain biscuits were provided between samples to cleanse the palate and minimise carry-over effects [29].

2.6 Statistical analysis

Physicochemical measurements were performed in duplicate and expressed as mean ± standard deviation. One-way analysis of variance (ANOVA) followed by Tukey's honestly significant difference (HSD) post-hoc test was performed in SPSS at $p < 0.05$. Sensory scores were expressed as mean ± standard deviation and compared among blends by one-way ANOVA followed by Tukey's HSD test at $p < 0.05$.

3. Results and Discussion

3.1 Changes in pH

Final pH values were 3.52 ± 0.02 for Blend A (strawberry-dominant, 40:60 golden berry:strawberry), 3.30 ± 0.02 for Blend B (balanced, 50:50), and 3.29 ± 0.02 for Blend C (golden berry-dominant, 60:40). All three values fell within the pH range typically reported for fruit wines (3.0–3.6), a range low enough to inhibit the growth of most spoilage bacteria and pathogenic organisms while remaining compatible with active *Saccharomyces cerevisiae* fermentation, but the values recorded here were slightly higher than those commonly reported for conventional, sugar-amended fruit wines, a pattern consistent with the moderated organic-acid production expected under a dry-fermentation regime that relies solely on the fruit's own, comparatively limited, fermentable-sugar pool.

Blend C recorded the lowest pH among the three formulations, consistent with the higher natural citric- and malic-acid content of golden berry relative to strawberry, whose principal organic acid, citric acid, is present at comparatively lower concentration and is partly buffered by the fruit's higher natural sugar and mineral content. Blend B, formulated at equal proportions of both fruits, stabilised at a mid-range value between Blends A and C, since the equal contribution of both fruits prevented either acid profile from dominating the final must chemistry [27, 28]. This intermediate acid character appears, based on the sensory results discussed in Section 3.6, to have been perceived by panelists as more balanced than either the milder acidity of Blend A or the sharper acidity of Blend C.

The moderated overall acidification across all three blends, relative to what might be expected from a sugar-amended formulation, likely reflects the more limited pool of fermentable carbohydrate available for yeast metabolism and, indirectly, for the accumulation of fermentation-derived organic acids such as succinic acid, which is produced by *Saccharomyces cerevisiae* as a minor by-product of sugar catabolism; with less sugar available overall, the contribution of such secondary acids to total measured acidity would be expected to be correspondingly smaller. Despite this moderation, the pH values achieved across all three formulations remained low enough to support microbial stability during the 21-day fermentation and subsequent storage, and contributed positively to the perceived freshness and balance of the finished wines, as reflected in the appearance and taste scores reported in Table 1.

From a food-safety and product-design perspective, the pH range achieved here is also relevant to the subsequent addition of potassium metabisulfite for stabilisation, since the antimicrobial efficacy of sulfite preservation is strongly pH-dependent, with the more active molecular form of sulfur dioxide favoured at lower pH; the comparatively low pH of all three blends, and particularly of Blend C, would therefore be expected to support more effective sulfite-based stabilisation at a given dosage than would a higher-pH formulation, an interaction worth confirming through future shelf-life trials specifically designed to test sulfite efficacy across the three blend ratios.

A re-analysis of these values by one-way ANOVA confirmed a significant overall effect of blending ratio on final pH ($F(2,3) = 84.50$, $p = 0.002$). Tukey's HSD post-hoc test indicated that Blend A differed significantly from both Blend B ($p = 0.003$) and Blend C ($p = 0.003$), whereas Blend B and Blend C were not significantly different from one another ($p = 0.877$); the corresponding compact-letter grouping (Aa,

Bb, Cb) is reported in Table 2, indicating that the strawberry-dominant formulation was the principal driver of the pH differences observed among blends, rather than golden berry proportion per se.

3.2 Changes in total soluble solids (°Brix)

Final apparent °Brix values were 0.50 ± 0.07 for Blend A, 0.30 ± 0.06 for Blend B, and 0.20 ± 0.05 for Blend C. The progressive decline in °Brix recorded across all three blends over the 21-day fermentation period indicates active and sustained metabolism of soluble fermentable sugars by *Saccharomyces cerevisiae*, consistent with the dry-fermentation objective of the study, in which no external sugar was added and fermentation was allowed to proceed until residual sugar fell below 1 g/L.

Blend A began fermentation with the highest initial °Brix, a pattern attributable to the naturally high sugar content of strawberry, which is rich in readily fermentable glucose, fructose and sucrose, whereas Blend C began with the lowest initial °Brix because golden berries are comparatively less sweet on a fresh-weight basis and contribute a higher proportion of organic acids relative to sugars. Golden berry's citric- and malic-acid content also depresses refractometer readings independently of sugar concentration, since refractometric °Brix measures total dissolved solids rather than sugar specifically, meaning that part of the lower apparent °Brix recorded for golden berry-dominant blends reflects their acid profile as well as their genuinely lower sugar content; despite this, golden berry's reducing sugars are known to ferment comparatively rapidly once yeast populations are established, supporting efficient sugar depletion even in the golden berry-dominant Blend C.

Blend B showed an intermediate pattern of sugar consumption consistent with its equal-proportion formulation, reflecting a combination of strawberry's sucrose- and glucose-dominant contribution and golden berry's smaller but still fermentable sugar fraction; the resulting final °Brix of 0.30 ± 0.06 places Blend B between the higher residual value of Blend A and the lower residual value of Blend C, broadly in line with what would be expected from a simple compositional average of the two parent juices, modulated by any differences in fermentation rate between the three musts.

The consistently low final °Brix values recorded across all three blends, all well below 1°Brix, are consistent with the study's low-sugar design objective and support the classification of the finished wines as dry, in the technical winemaking sense of the term, prior to the deliberate reintroduction of sweetness through post-fermentation stevia addition. This pattern aligns with the broader principle, well established in fermentation science, that sugar depletion is a key indicator of both fermentation progress and eventual product stability, since residual fermentable sugar remaining in an otherwise stabilised wine represents a potential substrate for renewed microbial activity if storage conditions or sulfite dosing are inadequate [7, 29]. The near-complete sugar depletion achieved in all three blends therefore represents not only compliance with the study's diabetic-friendly design brief but also a favourable starting point for microbiological stability during subsequent storage.

One-way ANOVA indicated a significant overall effect of blending ratio on final °Brix ($F(2,3) = 12.73$, $p = 0.034$); however, Tukey's post-hoc test showed that only the two compositional extremes differed

significantly from one another (Blend A vs Blend C, p = 0.032), while Blend B could not be statistically distinguished from either Blend A (p = 0.090) or Blend C (p = 0.354), consistent with its intermediate compositional position (compact letters Aa, Bab, Cb; Table 2).

3.3 Changes in alcohol content (% ABV)

Alcohol content reached 10.25 ± 0.07% ABV in Blend A, 10.05 ± 0.07% ABV in Blend B, and 9.85 ± 0.07% ABV in Blend C, increasing progressively across the 21-day fermentation period in all three blends as *Saccharomyces cerevisiae* metabolised the fruits' natural fermentable sugars into ethanol and carbon dioxide via glycolysis and subsequent alcoholic fermentation.

The gradient observed across the three blends, from the highest alcohol content in the strawberry-dominant Blend A to the lowest in the golden berry-dominant Blend C, mirrors the initial °Brix gradient discussed in Section 3.2 and is consistent with the stoichiometric relationship between initial fermentable-sugar concentration and final ethanol yield that underlies alcoholic fermentation generally: a must with a higher initial sugar load will, all else being equal, support a correspondingly higher final alcohol concentration, provided fermentation proceeds to completion and yeast viability is not limiting. Blend A's higher alcohol content therefore reflects the higher fermentable-sugar contribution of strawberry [30], while Blend C's comparatively lower alcohol content reflects golden berry's lower sugar but higher organic-acid contribution; Blend B's intermediate value is consistent with its equal-proportion composition.

All three alcohol values fell within the typical consumer-acceptable range reported for fruit wine (approximately 8–15% ABV) [31, 32], and the differences among blends, while statistically distinguishable given the small standard deviations reported, are modest in absolute terms and unlikely, on their own, to represent a major driver of the sensory differences discussed in Section 3.6; the more pronounced sensory differentiation among blends is more plausibly attributable to differences in acid, aroma-compound and colour composition than to the roughly 0.4-percentage-point spread in alcohol content across formulations.

An alcohol content in the region of 10% ABV is nonetheless a relevant consideration for the diabetic-friendly positioning of this product, since alcohol consumption can suppress hepatic glycogenolysis and gluconeogenesis, the two principal pathways by which the liver maintains blood glucose during fasting periods, thereby increasing the risk of delayed hypoglycaemia, particularly in individuals using insulin or insulin-secretagogue medications such as sulfonylureas, and particularly when alcohol is consumed without accompanying food [33, 34]. This physiological interaction means that, notwithstanding the product's low residual-sugar formulation, moderate and informed consumption remains an important part of how any eventual diabetic-friendly positioning of this wine should be communicated to consumers, and reinforces the conclusion, developed further in Section 4, that the product is best regarded at this stage as a lower-sugar alternative within a broader moderation framework rather than as a beverage without metabolic considerations for people living with diabetes.

Final alcohol content likewise differed significantly among blends overall (one-way ANOVA, $F(2,3) = 16.33$, $p = 0.024$), although, as for °Brix, only the strawberry-dominant Blend A and golden berry-dominant Blend C differed significantly from each other (Tukey HSD, $p = 0.022$); Blend B could not be statistically distinguished from either extreme ($p = 0.126$ in both comparisons; compact letters Aa, Bab, Cb; Table 2), reinforcing the interpretation that the modest overall ABV spread across formulations is compositionally graded rather than sharply discontinuous between adjacent blending ratios.

3.4 Changes in total titratable acidity

Titratable acidity values were 6.55 ± 0.07 g/L, 6.1 ± 0.07 g/L, and 6.85 ± 0.07 g/L for Blends A, B and C, respectively, expressed as g/L equivalent following the RS EAS 104 titration procedure described in Section 2.4.

Blend C's higher titratable acidity is attributable to the greater citric- and malic-acid contribution of golden berry, which preserved a more pronounced tartness through fermentation and storage, whereas Blend A's strawberry-dominant composition contributed a moderate acid load alongside a higher sugar content that would have partially masked acid perception even where measured titratable acidity was not itself the lowest of the three blends. The equal-ratio Blend B balanced the comparatively milder acid profile of strawberry with the sharper, more citrus-like acidity of golden berry, stabilising titratable acidity at the lowest, and by panelist report the smoothest-tasting, level among the three formulations.

Consistent with the pH results discussed in Section 3.1, Blend C combined the highest titratable acidity with the lowest pH, confirming golden berry's dominant contribution to the wine's overall acidic character and illustrating the expected inverse relationship between titratable acidity, a measure of total titratable organic-acid content, and pH, a measure of free hydrogen-ion activity; the two parameters are related but not interchangeable, since pH also reflects the buffering capacity of the must, including its mineral and protein content, and this is one reason the two measurements are conventionally reported together in wine analysis rather than either being used alone. Notably, Blend B's comparatively lower titratable acidity, relative to Blend C, coincided with the highest taste and overall-acceptability scores recorded in the sensory panel (Section 3.6), suggesting that the equal-ratio formulation achieved a more favourable acid–sweetness balance for the untrained consumer panel used in this study than either the more strawberry-forward or more golden-berry-forward alternatives.

Titratable acidity also carries direct relevance for microbial and chemical stability during storage, since organic acids such as citric and malic acid contribute, alongside low pH, to the inhibition of spoilage organisms and to the wine's resistance to oxidative browning; the comparatively acidic profile achieved across all three blends, and especially in Blend C, is therefore likely to be advantageous for shelf stability even where it was perceived, in the untrained sensory panel, as less favourable from a pure taste perspective. This tension between chemical stability and sensory preference is a common feature of fruit-wine formulation and underscores the value of considering titratable acidity, pH, and sensory acceptability jointly, as done in Section 3.7, rather than optimising for any single parameter in isolation.

Titratable acidity differed significantly among all three blends (one-way ANOVA, F(2,3) = 58.16, p = 0.004) and, unlike pH, °Brix and ABV, every pairwise Tukey comparison reached significance (Blend A vs Blend B, p = 0.016; Blend A vs Blend C, p = 0.047; Blend B vs Blend C, p = 0.004; compact letters Ab, Bc, Ca; Table 2). Titratable acidity was therefore the physicochemical parameter most sharply differentiated by blending ratio in this re-analysis, supporting its use, alongside pH, as a primary chemical discriminator of blend composition.

Table 2
One-way ANOVA summary of physicochemical parameters across golden berry-strawberry wine blends (n = 2 replicates per blend).

Parameter	Blend A (40:60)	Blend B (50:50)	Blend C (60:40)	F (df = 2,3)	p-value
pH	3.52 ± 0.02^{a}	3.30 ± 0.02^{b}	3.29 ± 0.02^{b}	84.50	0.002
°Brix	0.50 ± 0.07^{a}	0.30 ± 0.06^{ab}	0.20 ± 0.05^{b}	12.73	0.034
ABV (%)	10.25 ± 0.07^{a}	10.05 ± 0.07^{ab}	9.85 ± 0.07^{b}	16.33	0.024
TA (g/L)	6.55 ± 0.07^{b}	6.10 ± 0.07^{c}	6.85 ± 0.07^{a}	58.16	0.004

Means within a row followed by different superscript letters differ significantly (Tukey HSD, p < 0.05) following one-way ANOVA on the reported means and standard deviations (n = 2 replicate measurements per blend); see Section 3.8 *for the statistical-power limitations associated with this replicate number.*

3.5 Antioxidant activity

Antioxidant activity, expressed as ferric-reducing absorbance at 700 nm, increased with increasing golden berry proportion across the three blends: Blend A recorded the lowest activity (0.82 absorbance units), Blend B an intermediate value (0.95), and Blend C the highest (1.02), a range broadly consistent with values typically reported for functional or phenolic-enriched fruit wines assessed by similar ferric-reducing assays.

The ferric-reducing method used in this study operates on the principle that reducing agents present in the sample, including ascorbic acid, phenolic compounds and certain carotenoid-derived species, donate electrons to reduce the ferricyanide complex to its ferrous form, which subsequently reacts with ferric chloride to generate a Prussian-blue coloured complex whose absorbance at 700 nm is proportional to the sample's overall reducing capacity; higher absorbance therefore indicates a greater pool of electron-donating, and by extension potentially antioxidant, compounds in the sample, although it should be noted that this assay, in common with other single-electron-transfer-based methods, measures total reducing capacity rather than antioxidant activity against any one specific reactive oxygen or nitrogen species, and results should accordingly be interpreted as an indicator of overall redox activity rather than as a direct measure of physiological antioxidant efficacy.

The ascending order of absorbance across blends (A < B < C) indicates that a higher golden berry proportion was consistently associated with greater ferric-reducing power, consistent with golden berry's well-documented content of vitamin C, tocopherols, carotenoids and phenolic compounds, several of which are established contributors to in-vitro redox activity [35, 36]. In Blend C, the dominant golden berry fraction is likely to have contributed comparatively high levels of polyphenols, carotenoids and vitamin C, and the fruit's higher acidity may additionally have helped protect these antioxidant compounds from oxidative degradation during the 21-day fermentation, since low pH is generally associated with greater chemical stability of ascorbic acid and certain phenolic species. In Blend B, anthocyanins contributed by strawberry appear to have combined with carotenoids and citric acid contributed by golden berry to stabilise the overall polyphenolic pool, yielding an intermediate but still substantial antioxidant signal, while Blend A, being strawberry-dominant, contributed anthocyanins and vitamin C at comparatively lower absolute concentrations, consistent with its lower measured absorbance.

From a product-positioning perspective, the observed gradient in antioxidant activity is a relevant, though not sufficient, piece of evidence in support of this wine's diabetic-friendly framing, since oxidative stress is recognised as a contributing mechanism in the development of diabetes-related complications, and beverages or foods with a higher measured reducing capacity are sometimes marketed on this basis. It is important to note, however, that the ferric-reducing values reported here are in-vitro measurements on the finished wine matrix and do not, on their own, establish bioavailability, physiological antioxidant effect, or any clinical benefit in individuals with diabetes; any such claim would require dedicated bioavailability and, ultimately, clinical investigation beyond the scope of the present formulation and characterisation study, a limitation discussed further in Section 3.8.

Because antioxidant activity was recorded as a single mean value per blend without an accompanying replicate standard deviation, formal inferential testing (one-way ANOVA) could not be performed for this parameter as part of the present re-analysis, and the monotonic A < B < C pattern described above should therefore be read as a descriptive trend rather than a statistically confirmed difference. Reporting antioxidant activity from at least three independent replicates per blend in future work would allow this trend to be tested formally, a point developed further in Section 3.8.

3.6 Sensory acceptability

After 21 days of fermentation, stabilisation and stevia sweetening, appearance, taste, flavour, aroma and overall acceptability were evaluated by a panel of 15 untrained panelists using a 5-point hedonic scale, in which higher scores denote greater liking. Blend B received the highest mean scores across all five attributes assessed (Table 1), indicating that the equal-ratio, 50:50 golden berry:strawberry formulation was consistently preferred over both the strawberry-dominant Blend A and the golden berry-dominant Blend C.

For appearance, Blend B was rated 4.6 ± 0.3, reflecting a balanced reddish hue produced by the roughly equal contribution of strawberry anthocyanins and golden berry carotenoids, compared with 4.2 ± 0.2 for

Blend A and 4.0 ± 0.3 for Blend C, whose higher golden berry proportion produced a more yellowish-orange tone that appears to have been somewhat less appealing to the panel than the more familiar red-toned wine colour typically associated with fruit wines in this consumer context. Colour is well established in food-sensory science as an important driver of initial product expectation, and the relatively strong appearance scores recorded for Blend B likely contributed positively to subsequent taste and flavour ratings through an expectation-confirmation effect commonly observed in hedonic testing.

For taste, Blend B again scored highest (4.4 ± 0.3), reflecting a balanced sweetness–acidity profile, consistent with the lowest titratable acidity and intermediate pH values discussed in Sections 3.1 and 3.4, together with a smoother overall mouthfeel, compared with 3.9 ± 0.2 for Blend A and 3.5 ± 0.2 for Blend C. The comparatively lower taste score for Blend C is consistent with the more pronounced tartness contributed by its higher golden berry proportion, which, while favourable from an antioxidant and microbial-stability standpoint (Sections 3.4–3.5), appears to have exceeded the threshold of acid intensity preferred by this untrained consumer panel, particularly once combined with the mild, sometimes lingering aftertaste characteristic of stevia at the concentrations used for post-fermentation sweetening.

A similar pattern was observed for flavour, with Blend B again scoring highest (4.5 ± 0.2), followed by Blend A (4.0 ± 0.2) and Blend C (3.7 ± 0.3); panelists' qualitative comments, recorded informally during evaluation, noted that the perceived synergy between strawberry's fruity, ester-derived notes and golden berry's characteristic tartness produced a richer and more complex overall flavour impression in the equal-ratio blend than in either single-fruit-dominant formulation, consistent with the general principle in fruit-blend product development that complementary rather than dominant fruit pairings often maximise perceived flavour complexity. For aroma, Blend B again scored highest (4.3 ± 0.3), followed by Blend C (3.9 ± 0.2) and Blend A (3.6 ± 0.2); this ordering, in which Blend C outperformed Blend A on aroma despite scoring lowest on taste, may reflect more effective retention or generation of volatile aroma esters in the balanced formulation during active fermentation, possibly linked to the moderating effect of golden berry's acidity on yeast ester metabolism, an interaction that would benefit from confirmation using volatile-compound profiling such as gas chromatography–mass spectrometry in future work.

Overall acceptability followed the same trend observed across the individual attributes, with Blend B scoring highest (4.6 ± 0.3), compared with 4.2 ± 0.2 for Blend A and 3.8 ± 0.2 for Blend C. Together, these results indicate that blending ratio is a key determinant of sensory quality in golden berry–strawberry co-fermented wine, and that the equal-ratio formulation (Blend B) offers the most consumer-acceptable balance of colour, taste, flavour and aroma among the three formulations tested, while remaining suitable, on the basis of its physicochemical profile, for consumers managing diabetes risk. It should be noted that the panel used in this study was untrained and relatively small (n = 15), drawn from a single age range and geographic context; while such panels are appropriate for an initial, exploratory acceptability assessment of a novel formulation, the sensory findings reported here should be confirmed

with larger and, where product claims are intended, more demographically representative panels before firm commercial or public-health messaging is developed around any specific blend.

Table 1
Sensory evaluation scores (5-point hedonic scale) of golden berry–strawberry wine blends after 21 days of fermentation and stevia sweetening.

Sensory attribute	Blend A (40:60) Mean ± SD	Blend B (50:50) Mean ± SD	Blend C (60:40) Mean ± SD
Appearance	4.2 ± 0.2^{b}	4.6 ± 0.3^{a}	4.0 ± 0.3^{b}
Taste	3.9 ± 0.2^{b}	4.4 ± 0.3^{a}	3.5 ± 0.2^{c}
Flavour	4.0 ± 0.2^{b}	4.5 ± 0.2^{a}	3.7 ± 0.3^{c}
Aroma	3.6 ± 0.2^{c}	4.3 ± 0.3^{a}	3.9 ± 0.2^{b}
Overall acceptability	4.2 ± 0.2^{b}	4.6 ± 0.3^{a}	3.8 ± 0.2^{c}

Means within a row followed by different superscript letters differ significantly (Tukey HSD, $p < 0.05$) following one-way ANOVA ($n = 15$ panelists per blend).

3.7 Integration of physicochemical and sensory findings

Considered together, the physicochemical and sensory results point consistently toward the equal-ratio Blend B as the most technically and commercially promising formulation among the three golden berry–strawberry blends evaluated. Blend B occupied an intermediate position for pH, °Brix and alcohol content, between the more strawberry-forward Blend A and the more golden berry-forward Blend C, and recorded the lowest titratable acidity of the three formulations; this combination of moderate chemistry and softened acidity translated directly into the highest sensory scores recorded across all five hedonic attributes. This convergence is consistent with a well-established principle in food and beverage sensory science, sometimes summarised as the just-about-right, or optimum-balance, phenomenon, in which consumer liking for attributes such as sweetness, acidity or intensity tends to peak at an intermediate level rather than increasing monotonically with the concentration of any single compositional driver; in the present study, this pattern manifested as a clear preference for the balanced acid, colour and aroma profile achieved when golden berry and strawberry were combined in equal proportion, over the more one-sided sensory profiles produced by either fruit-dominant blend.

The antioxidant results present a partial exception to this pattern, since ferric-reducing activity increased monotonically with golden berry proportion rather than peaking at the balanced ratio, meaning that Blend C, despite its comparatively lower sensory scores, delivered the highest measured antioxidant signal of the three formulations. This divergence between the sensory-optimal and antioxidant-optimal formulations illustrates a common trade-off in functional-beverage development, in which the compositional changes that maximise a specific functional attribute do not necessarily coincide with

those that maximise consumer acceptability, and it reinforces the conclusion that Blend B represents a balanced compromise, combining strong, though not maximal, antioxidant activity with the best overall sensory performance, rather than representing an unambiguous optimum on every single parameter measured.

The statistical structure underlying these physicochemical differences was not uniform across parameters: titratable acidity differentiated all three blends significantly from one another, pH separated the strawberry-dominant blend from the other two, while °Brix and ABV distinguished only the two compositional extremes (Table 2). This pattern helps explain why sensory perception, which integrates several of these dimensions simultaneously, tracked most closely with titratable acidity and pH, the two parameters showing the sharpest statistical separation, rather than with alcohol content or residual sugar alone.

From a diabetic-friendly product-design perspective, the combination of near-complete sugar depletion (final °Brix below 1° across all blends), moderate alcohol content within the typical fruit-wine range, and appreciable ferric-reducing antioxidant activity supports the overall technical feasibility of the dry-fermentation-plus-stevia-sweetening approach used in this study, while the sensory results confirm that this technical feasibility need not come at the cost of consumer acceptability, provided the blending ratio is chosen with sensory as well as compositional considerations in mind. These findings collectively support the selection of the equal-ratio Blend B as the lead candidate formulation for further development, while also illustrating, through the antioxidant results specifically, that alternative blending ratios such as Blend C may warrant separate consideration in product lines where functional antioxidant content, rather than broad sensory appeal, is the primary design objective.

3.8 Limitations and directions for further research

Several limitations of the present study should be acknowledged when interpreting these findings. First, physicochemical measurements were performed in duplicate rather than in triplicate or across independent fermentation batches, which, while consistent with common practice in exploratory formulation studies, limits the statistical power available to detect smaller differences between blends and means that the reported standard deviations should be interpreted as indicative of measurement precision within a given fermentation run rather than as a full estimate of batch-to-batch variability. Second, the sensory panel comprised 15 untrained panelists drawn from a single age range (18–45 years) and geographic context, a design appropriate for an initial acceptability screening but insufficient, on its own, to support broad claims about consumer acceptance across the more demographically diverse population, including older adults who represent a substantial share of the diabetes-affected population, that this product is ultimately intended to serve. It is also worth noting that, because physicochemical measurements were based on only two replicates per blend, the one-way ANOVA and Tukey HSD comparisons reported in Sections 3.1–3.4 rest on only three residual degrees of freedom, which constrains statistical power; non-significant pairwise comparisons obtained in this re-analysis (for example, Blend B versus Blend C for pH, or Blend A versus Blend B for °Brix and ABV) should accordingly be interpreted as inconclusive rather than as firm evidence of equivalence, and a larger number of

independent fermentation batches would allow these comparisons to be tested with greater confidence in future work.

Third, the antioxidant activity results reported here are based on a single ferric-reducing assay conducted on the finished wine matrix; complementary assays capturing different mechanisms of antioxidant action, such as radical-scavenging assays, together with quantification of specific phenolic and carotenoid compounds by chromatographic methods, would strengthen confidence in the functional claims associated with this product and are recommended for future work. Fourth, no volatile-compound profiling, for example by gas chromatography–mass spectrometry, was conducted in this study, meaning that the aroma-related interpretations offered in Section 3.6 remain inferential rather than directly measured, and future work incorporating such profiling would help clarify the specific compounds responsible for the aroma differences observed among blends. Fifth, and most importantly given the product's intended positioning, no shelf-life stability data, microbiological safety testing beyond the immediate post-fermentation period, or clinical glycaemic-response data in human subjects were collected as part of this study; the diabetic-friendly framing used throughout this manuscript should therefore be understood as reflecting the product's low-residual-sugar compositional profile rather than any demonstrated clinical outcome, and no health claim beyond reduced sugar content should be made on the basis of the present data alone.

Addressing these limitations through larger, more demographically representative sensory panels, expanded and orthogonal antioxidant and phenolic characterisation, dedicated shelf-life and microbiological stability trials, and, ultimately, appropriately designed clinical glycaemic-response studies represents a clear and necessary pathway for translating the promising formulation-level findings of this study into a validated, market-ready, diabetic-conscious beverage product.

3.9 Relevance to Rwanda's fruit and beverage value chain

Beyond its immediate physicochemical and sensory findings, this study carries practical relevance for Rwanda's fruit and beverage value chain, where both golden berry and strawberry are grown by smallholder farmers who frequently face limited market access, price volatility, and substantial postharvest losses for produce that is not consumed or sold within a short window of harvest. Fermentation-based processing of the kind demonstrated here offers a means of extending the effective shelf life of these fruits well beyond that of the fresh product, converting a perishable, low-value raw material into a higher-value, more storable finished beverage, and thereby offering smallholder producers and small-scale processors an additional route to market for fruit that might otherwise be sold at a discount or lost altogether.

The specific technical choices made in this study, namely dry fermentation without added sugar, followed by post-fermentation sweetening with a low-cost, locally available non-nutritive sweetener, are also relevant to the practical constraints faced by small-scale processors in Rwanda and similar settings, since this approach avoids the need for imported sugar-substitute technologies or specialised low-alcohol fermentation equipment, relying instead on standard fermentation vessels, a commercial wine

yeast already available through existing suppliers, and stevia extract obtainable from local retail outlets. This relative simplicity supports the technical feasibility of scaling the equal-ratio Blend B formulation identified in this study within existing small- and medium-scale processing infrastructure, subject to the further validation work on shelf-life, hygiene, and quality-standard compliance discussed in Section 3.8, and subject to appropriate regulatory engagement given that the finished product is an alcoholic beverage subject to relevant national standards and licensing requirements.

Finally, it is worth situating these results within the broader category of low- and reduced-alcohol, reduced-sugar beverage innovation more generally, a category in which reformulation efforts frequently encounter a similar tension to the one observed here between the compositional changes needed to achieve a functional or health-oriented objective and the sensory expectations that consumers bring to an established beverage category such as wine. The present findings suggest that, at least for the golden berry–strawberry pairing and the dry-fermentation-plus-stevia approach tested, this tension can be substantially, if not entirely, resolved through careful selection of blending ratio, with the equal-ratio Blend B offering a sensory profile that panelists rated favourably across every attribute assessed, despite the absence of any added fermentable sugar in the finished product. This outcome is encouraging for the broader proposition that diabetic-friendly reformulation of traditional fruit-wine categories need not entail a substantial sensory compromise, provided the underlying fruit composition is optimised with both chemical and sensory objectives explicitly in view from the outset of formulation work, rather than sensory evaluation being treated as a downstream confirmatory step applied only after a single fixed formulation has already been selected on compositional grounds alone.

4. Conclusion

A diabetic-friendly golden berry–strawberry wine was successfully produced by dry co-fermentation followed by stevia sweetening, yielding formulations with attractive physicochemical, antioxidant and sensory characteristics without added fermentable sugar. Strawberry contributed sugars, vitamin C and phenolic compounds, while golden berry contributed carotenoids, polyphenols and organic acids associated with antioxidant activity and tartness; combined, the two fruits produced a visually appealing wine with balanced colour, flavour, and functional potential.

The equal-ratio formulation (Blend B, 50:50 golden berry:strawberry) achieved the highest overall acceptability (4.6 ± 0.3), moderate alcohol content (10.05% ABV), and the best sensory scores across appearance, taste, flavour and aroma, indicating that it represents the most promising candidate for further development. The findings support the technical feasibility of combining dry fermentation and post-fermentation stevia sweetening to reduce residual sugar in fruit wine while maintaining consumer acceptability. The product should nonetheless be regarded as an experimental, stevia-sweetened low-sugar wine prototype rather than a clinically validated diabetic beverage; further work on shelf-life stability, larger-scale sensory validation, and clinical glycaemic-response assessment is recommended before any health claims are made. Scaling the equal-ratio formulation under controlled hygiene and quality standards, and exploring other underutilised local fruits for similar diabetic-friendly formulations,

are recommended directions for future research and value-addition in Rwanda's fruit and beverage sector.

Abbreviations

ABV — Alcohol by volume

ANOVA — Analysis of variance

°Brix — Degrees Brix (measure of total soluble solids)

g/L — Grams per litre

GC–MS — Gas chromatography–mass spectrometry

HSD — Honestly significant difference

mL — Millilitre

N — Normality (of a titrant solution)

NaOH — Sodium hydroxide

$\mathbf{N_B}$ — Normality of sodium hydroxide (titration formula variable)

nm — Nanometre

OIV — International Organisation of Vine and Wine

pH — Potential of hydrogen (measure of acidity/alkalinity)

RS EAS — Rwanda Standard, East African Standard (Rwanda Standards Board test method series)

SD — Standard deviation

SPSS — Statistical Package for the Social Sciences

TA — Titratable acidity

UV — Ultraviolet

$\mathbf{V_B}$ — Volume of sodium hydroxide used in titration (titration formula variable)

$\mathbf{V_S}$ — Volume of sample (titration formula variable)

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Data availability: The data supporting the findings of this study are available from the corresponding authors upon reasonable request (gisubizofabien@gmail.com).

Ethics approval and consent to participate: This study, including the sensory evaluation involving human participants, was approved by the Research Committee of the Institut d'Enseignement Supérieur de Ruhengeri (INES-Ruhengeri) on 23 January 2026 in accordance with the guidelines and regulations set forth by the Declaration of Helsinki and the national research ethics requirements of Rwanda. The protocol number for this approval is INES/AC/RW/0978. The sensory evaluation was conducted with adult volunteer panelists who provided verbal informed consent prior to tasting coded wine samples under standard food-sensory-panel conditions; no personal or identifying data were collected.

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