



Toxicological risk profiles in suicide: The forensic value of hair-based substance detection[☆]

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ARTICLE INFO

Keywords:

Suicide
Suicide risk profiles
Hair analysis
Substance abuse
Alcohol abuse
Suicide prevention

ABSTRACT

Introduction: Suicide is a major global cause of premature mortality and a critical public health concern. Chronic alcohol misuse and illicit drug use are well-established risk factors, but conventional post-mortem toxicology frequently fails to detect long-term substance exposure. Hair analysis represents a valuable forensic tool, enabling the reconstruction of pre-mortem behavioral patterns and offering insight into chronic substance use and its association with suicidal behavior.

Materials and methods: This retrospective study examined 74 suicide cases (59 males, 15 females) from 2023 to 2024. Hair samples were analyzed for ethyl glucuronide to assess chronic alcohol consumption and screened for psychoactive substances. Demographic data, previous suicide attempts, and methods of suicide were also considered.

Results: Chronic excessive alcohol use was identified in 75.7% of cases, with higher prevalence in females (93.3%) and individuals aged ≥ 65 years (88.9%). Illicit drugs were detected in 25.7% of cases, mainly cocaine (23.0%) and cannabis (17.6%). Polydrug use was found in 66.2% of subjects. Psychoactive drugs were frequently present: benzodiazepines in 63.5%, antidepressants in 36.5%, and antipsychotics in 10.8%. A prior suicide attempt was reported in 23.0% of individuals, with the highest rate among adolescents and young adults (29.4%).

Discussion and conclusion: These findings highlight age- and sex-specific toxicological patterns and support the forensic relevance of hair analysis in detecting chronic substance use. Integrating toxicological, clinical, and demographic data enhances post-mortem risk profiling and informs suicide prevention strategies targeting high-risk, underserved populations.

1. Introduction

Suicide represents a major global public health concern, significantly contributing to premature mortality across all regions of the world. According to the World Health Organization's (WHO) 2024 report, more than 800,000 individuals die by suicide each year, accounting for approximately one in every 100 deaths globally [1]. This corresponds to an estimated worldwide suicide rate of 9.9 per 100,000 people, with one suicide occurring every 40 s [2]. Suicide has become the 15th major

cause of death globally, and it remains the fourth leading cause of death among individuals aged 15 to 29 years [1]. Nonetheless, the true extent of suicide is likely underestimated, owing to factors such as reporting biases, societal stigma, and diagnostic misclassification in official mortality records [3]. Such underreporting is particularly pronounced in low- and middle-income countries, where civil registration and vital statistics systems are frequently incomplete, unreliable, or altogether absent [4]. Focusing on national data, the Italian Istituto Superiore di Sanità (ISS) reports that approximately 4,000 suicide deaths occur

[☆] This article is part of a special issue entitled: 'Proceedings Congress Forensic Science' published in Legal Medicine.

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<https://doi.org/10.1016/j.legalmed.2026.102805>

Received 27 July 2025; Received in revised form 2 January 2026; Accepted 1 February 2026

Available online 2 February 2026

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annually in Italy [4]. Furthermore, data from the Italian National Institute of Statistics (ISTAT) highlight a marked gender disparity: 78.8% of suicide deaths involve males, with a crude male suicide mortality rate of 11.8 per 100,000 inhabitants, compared to a substantially lower rate of 3.0 per 100,000 among females [5]. From a biological perspective, research has identified a genetic predisposition to suicidal behavior, with specific genes, such as neurexin-1, being associated with an elevated risk of suicide [6]. Mental disorders are a well-established risk factor, with mood disorders, including major depressive disorder and bipolar disorder, significantly increasing vulnerability by intensifying symptoms such as hopelessness, despair, and emotional dysregulation [7]. Beyond individual predispositions, contextual factors play a crucial role. Adverse childhood experiences, such as physical, emotional, or sexual abuse, as well as neglect, alongside a family history of psychiatric illness, are associated with a significantly increased risk of suicidal ideation [8]. Economic hardships, including financial distress and unemployment, have been strongly correlated with higher suicide rates, reinforcing perceptions of entrapment and failure [9]. The risk is further amplified by exposure to suicidal behavior, whether through personal connections or media portrayals, which can trigger imitative behaviors, particularly among adolescents and vulnerable individuals [7]. While it is impossible to identify a single triggering element as the primary cause of suicide, research consistently shows that people with drug use disorders are more likely to have suicidal thoughts and attempts [10]. Individuals who are dependent on or misuse alcohol or drugs are nearly six times more likely to attempt suicide compared to the general population [11].

Recent studies indicate people with substance use behavior (SUD) may be more prone to suicide thoughts and actions if they abuse or use certain substances. Specifically, individuals who use opioids, cocaine, or sedative-hypnotics exhibit significantly elevated rates of suicidal behavior compared to those who use other substances [12]. In people with alcohol use disorder (AUD), increased frequency and intensity of recent alcohol consumption are closely correlated with both suicide attempts and completed suicides [13]. Furthermore, the co-occurrence of alcohol and other drug use disorders appears to confer an additive or even synergistic effect, resulting in a markedly elevated risk profile for suicidal behavior [14]. Therefore, the severity of substance use disorders, reflected by the number of substances used or by the concurrent use of multiple substances, may be considered a predictive factor for an increased risk of suicide [15]. From a neurobiological standpoint, chronic substance use may contribute to suicide vulnerability through mechanisms such as dysregulation of the hypothalamic-pituitary-adrenal axis, impaired serotonergic neurotransmission, and structural brain alterations that impair emotional regulation and impulse control [16]. These alterations, in combination with substance-induced cognitive distortions and pre-existing psychosocial adversities, often create a cumulative and progressive risk behavior.

Despite the well-established association between substance use and suicidal behavior, conventional toxicological analyses, primarily based on blood or urine, are inherently limited to detecting recent substance intake within a narrow temporal window preceding death, thereby hindering the reconstruction of long-term exposure patterns that may have contributed to the suicidal act [17].

Considering these limitations, the present study aims to provide a more comprehensive and temporally extended evaluation of substance use preceding suicide by employing hair analysis. Due to its keratinous composition, hair allows for the retrospective reconstruction of drug and alcohol use over a period of several weeks to months [17]. This analytical approach provides a more comprehensive overview of chronic substance exposure, allowing for the detection of licit and illicit drugs, alcohol, and psychoactive medications. Therefore, the objective of this study is to investigate potential correlations between long-term substance use patterns and suicide, with particular attention to variations across demographic factors such as gender, age, and the method of suicide employed. By providing a deeper understanding of the

toxicological profiles associated with suicidal behavior, the findings may contribute to the development of more effective prevention strategies targeting substance-related risk factors. From a medico-legal perspective, integrating hair toxicology into routine post-mortem investigations may enhance the accuracy of death certification, support the identification of substance-related vulnerabilities in suicidal individuals, and improve the interpretation of behavioral dynamics preceding death.

2. Materials and methods

2.1. Study population and sample collection

This study was conducted in accordance with the ethical standards of the Declaration of Helsinki (1975, revised 1983) and was approved by the Bioethics Review Board of the University of XXX (Protocol No. 56/2023). The study population consisted of 74 individuals (59 males and 15 females), aged between 13 and 96 years, who died by suicide between 2023 and 2024. Hair samples or pubic hair, when head hair was unavailable, were collected.

Samples were collected during judicial autopsies and/or external cadaveric inspections performed by forensic medical consultants. The samples were cleaned, if necessary, sealed in envelopes labeled with a unique alphanumeric code, and promptly transferred to the Forensic Toxicology Laboratory of the University of Perugia for analysis.

The length of the keratinic material ranged from 2 cm to 40 cm, with a mean of 7.09 cm (SD = 6.97). The median length was 4.5 cm, with an interquartile range (IQR) of 3–7 cm.

Demographic data (e.g., gender, age), circumstantial information (e.g., chronic pathologies, previous suicide attempts, environmental stressors), and the method of suicide were recorded.

2.2. Reagents and chemicals

All reagents and solvents were of analytical grade. Certified reference drug standards and deuterated internal standards were obtained from Merck (Milan, Italy).

2.3. Preparation and analysis of hair samples

A 50 mg sample of head or pubic hair was used for toxicological screening for illicit drugs, prescription medications, and chronic alcohol consumption through the detection of ethyl glucuronide (EtG).

All samples were prepared, extracted, and derivatized following previously described validated method [18]. The analytical determination was carried out using a triple quadrupole gas chromatography–mass spectrometry system (GC–MS/MS, Agilent 7000C) coupled with a 7890B gas chromatograph (Agilent Technologies, Palo Alto, CA, USA), operated in electron ionization (EI) mode.

Chromatographic separation was achieved using an HP-5MS capillary column (30 m × 0.25 mm i.d., 0.25 μm film thickness), with helium as the carrier gas at a flow rate of 1 mL/min. The temperature program was set as follows: initial temperature at 80 °C (1 min), ramped at 8 °C/min to 300 °C, and held for 2 min. Samples (1 μL) were injected in splitless mode (1 min) at 250 °C. The ion source and auxiliary (AUX) temperatures were set at 250 °C and 280 °C, respectively.

Mass spectrometric acquisition for unknown substances was performed in full-scan mode over a mass range of 41–500 amu. Identification was achieved by matching the obtained spectra with entries in the NIST spectral library. The determination of EtG was performed in multiple reaction monitoring (MRM) mode, using precursor ion m/z 261 [18].

2.4. Statistical analysis

Descriptive statistics were applied to summarize the characteristics

of the dataset. Categorical variables were reported as absolute frequencies and percentages, while continuous variables were expressed as means \pm standard deviations (SD) for normally distributed data, or medians with interquartile ranges (IQR) for non-normally distributed data. The normality of continuous variables was assessed using the Shapiro–Wilk test. For group comparisons, parametric or non-parametric tests were applied as appropriate: one-way repeated-measures analysis of variance (ANOVA) was used for normally distributed continuous variables, whereas the Kruskal–Wallis test was employed for non-parametric alternatives. Associations between categorical variables were evaluated using the chi-square (χ^2) test or Fisher’s exact test when expected cell counts were less than 5. A two-tailed p-value of < 0.05 was considered statistically significant. All statistical analyses were performed using STATA software, version 14.1 (StataCorp LP, College Station, TX, USA).

For the purpose of this study, polydrug use was defined as the concurrent detection of at least two different psychoactive substances in hair, irrespective of their classification as licit or illicit. This included combinations of illicit drugs (e.g., cocaine, cannabis), prescription psychotropic medications (e.g., benzodiazepines, antidepressants, antipsychotics), or both. The presence of a single medication alone (such as an antidepressant without other substances) was not considered polydrug use.

3. Results

Descriptive characteristics of the study population ($n = 74$) are reported in Table 1. The study population was categorized into three age groups: adolescents and young adults (13–35 years), adults (36–64 years), and older adults (≥ 65 years). The majority of cases belonged to the adult group (52.7%, $n = 39$), followed by older adults (24.3%, $n = 18$) and adolescents/young adults (23.0%, $n = 17$). The sample was predominantly male (79.7%, $n = 59$), with the highest male representation among younger individuals (88.2%) and older adults (83.3%). Females accounted for 20.3% of the total sample ($n = 15$), with most cases occurring in the adult age group (66.7%, $n = 10$).

When analyzing the distribution of previous suicide attempts across age groups, it was observed that the majority of subjects (77.0%, $n = 57$) had no documented history of suicide attempts, while 23.0% ($n = 17$) had experienced at least one prior attempt.

Overall, 23.0% ($n = 17$) of the total sample had a documented history of prior suicide attempts. When analyzed by age group, these percentages refer to the proportion within each subgroup: 29.4% ($n = 5/17$) among adolescents and young adults (0–35 years), 23.1% ($n = 9/39$) among adults (36–64 years), and 16.7% ($n = 3/18$) among older adults (> 65 years). Although the relative proportion is higher among younger individuals, this difference was not statistically significant.

When analyzing the distribution of suicide methods within each subgroup, non-attempters ($n = 57$) most frequently died by hanging (31/57; 54.4%), followed by falling from height (9/57; 15.8%) and other methods (17/57; 29.8%). Among individuals with a previous suicide attempt ($n = 17$), hanging accounted for 7 cases (41.2%), falling from height for 3 cases (17.7%), and other methods for 7 cases (41.2%). No statistically significant association was observed between suicide method and history of previous attempts ($p > 0.05$; Fig. 1).

The category “other methods” comprised 24 cases. Detailed information on the specific suicide mechanism was available for 21 subjects, including firearm injury ($n = 9$), train impact ($n = 4$), ingestion of toxic substances ($n = 3$), drowning ($n = 1$), sharp force injury ($n = 1$), use of a captive bolt pistol ($n = 1$), carbon monoxide poisoning ($n = 1$), and plastic bag suffocation ($n = 1$).

Gender-based differences were also observed. Hanging was the most frequent method among both males (55.9%) and females (33.3%); however, females more often employed alternative methods (46.7%) compared to males (28.8%), suggesting a more varied pattern of suicidal behavior among women (Fig. 2).

Table 1

Demographic and case-specific characteristics of suicide victims ($n = 74$), including age, gender, method of suicide, and presence or absence of previous suicide attempts. Methods were categorized as hanging, fall from height, or other (e.g., firearm injury, ingestion of toxic substances, train impact, drowning, sharp force injury, captive bolt pistol use, carbon monoxide poisoning, or suffocation).

Case	Age	Gender	Suicide method	Previous attempts
1	45	M	Other	No
2	33	M	Fall from height	No
3	55	M	Other	No
4	96	M	Other	No
5	37	M	Hanging	No
6	45	F	Other	Yes
7	44	F	Other	No
8	53	M	Hanging	No
9	61	F	Other	Yes
10	50	F	Hanging	Yes
11	47	M	Hanging	No
12	55	F	Hanging	No
13	65	M	Hanging	No
14	40	M	Other	Yes
15	60	F	Other	No
16	65	M	Hanging	No
17	75	M	Other	No
18	53	M	Hanging	No
19	60	M	Fall from height	Yes
20	70	M	Hanging	No
21	58	M	Hanging	No
22	45	M	Hanging	No
23	35	M	Hanging	No
24	42	F	Hanging	No
25	61	M	Hanging	No
26	57	M	Hanging	No
27	25	M	Hanging	No
28	28	M	Hanging	No
29	48	M	Hanging	No
30	26	F	Other	Yes
31	80	M	Fall from height	Yes
32	35	M	Other	No
33	74	F	Other	No
34	60	M	Hanging	No
35	69	M	Other	No
36	40	M	Hanging	No
37	55	M	Hanging	No
38	28	M	Hanging	No
39	54	M	Other	No
40	30	M	Fall from height	No
41	65	M	Hanging	No
42	56	M	Hanging	No
43	39	M	Other	No
44	84	F	Fall from height	No
45	47	M	Hanging	No
46	76	M	Hanging	No
47	62	M	Fall from height	No
48	22	M	Other	No
49	50	M	Hanging	No
50	62	M	Other	No
51	82	F	Fall from height	Yes
52	41	M	Fall from height	No
53	68	M	Fall from height	No
54	32	M	Hanging	No
55	20	M	Hanging	Yes
56	16	M	Hanging	No
57	74	M	Other	No
58	54	M	Other	No
59	27	M	Other	No
60	24	M	Fall from height	No
61	86	M	Hanging	No
62	54	F	Hanging	No
63	61	M	Hanging	No
64	54	F	Other	No
65	13	F	Fall from height	No
66	69	M	Other	No
67	30	M	Hanging	No
68	69	M	Fall from height	No
69	52	M	Other	No

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Table 1 (continued)

Case	Age	Gender	Suicide method	Previous attempts
70	54	F	Hanging	No
71	40	M	Hanging	No
72	47	M	Other	Yes
73	30	M	Hanging	Yes
74	84	M	Hanging	No

Chronic alcohol consumption was assessed by measuring hair EtG concentrations, a validated biomarker indicative of the extent and pattern of alcohol intake [19]. As a minor ethanol metabolite detectable in various biological matrices including hair, EtG enables differentiation

between abstinence (EtG < 5 pg/mg) and chronic excessive intake (EtG > 30 pg/mg) according to internationally recognized thresholds [20]. Interestingly, EtG levels above 30 pg/mg were observed in 75.7% of cases (n = 56), highlighting a substantial prevalence of chronic excessive alcohol consumption within the cohort. EtG concentrations ranged from 18 to 84 pg/mg, with a mean value of 44.3 pg/mg, a median of 42 pg/mg, and a standard deviation of 16.3 pg/mg. The interquartile range (IQR) extended from 28 to 55 pg/mg, indicating a moderate dispersion of values and a clustering of cases within the range of high-risk drinking behavior. Among individuals exceeding the 30 pg/mg threshold, 33 (58.9%) showed EtG concentrations between 30 and 50 pg/mg, 17 (30.4%) between 50 and 70 pg/mg, and 6 (10.7%) above 70 pg/mg,

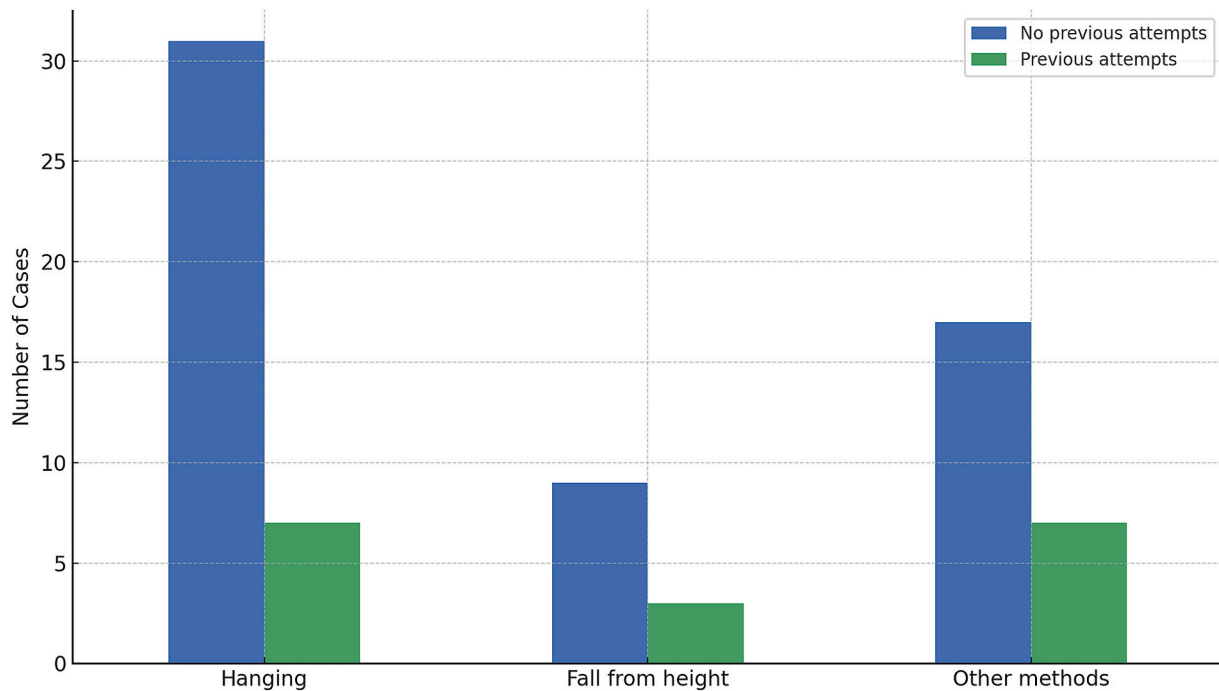


Fig. 1. Method of suicide by previous attempts.

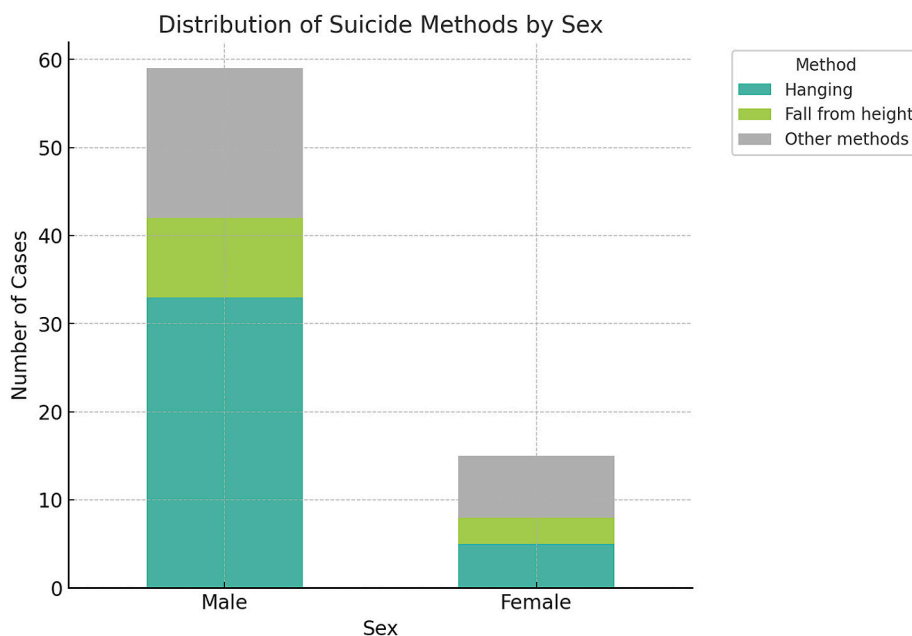


Fig. 2. Distribution of suicide methods by sex.

reflecting varying degrees of severity in chronic alcohol intake (Fig. 3). This pattern was particularly prevalent among older adults, especially in the ≥ 65 age group, where 88.9% exceeded the 30 pg/mg threshold. Although no statistically significant association emerged, higher EtG levels were also more frequently observed in subjects with prior suicide attempts (82.4%) and among those who died by hanging (78.9%) or by other modalities (79.2%) (Fig. 4). Regarding gender, high EtG levels were detected in 93.3% of females and 71.2% of males, suggesting a disproportionate prevalence of chronic alcohol use among women in the sample, despite their overall lower representation.

Toxicological analysis revealed a high prevalence of psychoactive medications: benzodiazepines were detected in 63.5% of cases, antidepressants in 36.5%, and antipsychotics in 10.8%. Opioid analgesics were found in 16.2% of individuals, and methadone were both detected in 9.5%. Among illicit substances, cocaine was the most frequently detected (23.0%), followed by cannabis (17.6%), heroin (9.5%), MDMA (8.1%), and ketamine (2.7%) (Fig. 5). Polydrug use was common: 31.1% of subjects tested positive for one substance, 37.8% for two, 23.0% for three, and 5.4% for four different substances. Analysis of the relationship between polydrug use and method of suicide showed that individuals with higher degrees of polydrug consumption were distributed across all suicide modalities. Specifically, among those with no polydrug use, two cases were recorded with methods other than hanging or fall. For subjects positive to one substance, hanging was the most frequent method ($n = 11$), followed by other methods ($n = 8$) and fall from height ($n = 4$). Those with two substances showed similar distribution with a predominance of hanging ($n = 14$), other methods ($n = 9$), and fall from height ($n = 5$). For individuals with three substances, hanging remained most common ($n = 10$), followed by other methods ($n = 4$) and fall ($n = 3$). Subjects with four substances mostly died by hanging ($n = 3$) or other methods ($n = 1$) (Fig. 6).

4. Discussion

This retrospective analysis of 74 suicide cases converges demographic, clinical, and toxicological variables that help define a high-risk profile for suicidal behavior. A greater occurrence of previous suicide attempts was observed among adolescents and young adults compared to older individuals. Although this trend did not reach statistical significance, it aligns with existing literature indicating a higher prevalence of non-fatal suicidal behaviors in younger populations, frequently associated with impulsivity, emotional dysregulation, and the onset or exacerbation of psychiatric disorders [21,22]. The absence of statistical significance supports earlier findings suggesting that, while a history of suicide attempts remains a relevant clinical marker, it may not act as an independent predictor of suicide risk across age groups

unless considered in the broader context of clinical and psychosocial factors [23].

Regarding methods of suicide, individuals without known prior attempts more frequently died by hanging or jumping from heights, whereas those with previous attempts used a wider range of methods. In contrast, those with previous attempts used a more varied range of methods, a pattern that appears consistent with the “method escalation” hypothesis described in the literature, which suggests a possible progression from less to more lethal strategies in recurrent suicidal behavior [24]. However, this interpretation should be considered cautiously, as the cross-sectional nature of this study does not allow confirmation of such a trajectory.

Gender differences were evident: although hanging was the most common method for both sexes, females more frequently employed alternative techniques such as ingestion of toxic substances, drowning, or carbon monoxide poisoning, consistent with well-documented gender-related differences in the choice of suicide methods [25].

A central element of the study concerns the toxicological profile of the decedents. Chronic excessive alcohol consumption, as evidenced by EtG levels above the established cut-off in hair, was commonly observed, particularly among males aged between 35 and 55 years and individuals with prior suicide attempts. These findings are consistent with the literature describing alcohol misuse as a key factor in suicidal vulnerability, through mechanisms involving impulsivity, cognitive impairment, and mood disorders [26,27].

Polydrug use, defined as the co-consumption of multiple psychoactive substances, was also identified. Within this group, male gender. In the majority of these cases, chronic alcohol misuse was also present. The most frequently co-detected substances included cocaine, cannabis, heroin, and benzodiazepines. These findings reflect a well-characterized high-risk profile marked by chronic substance dependence, emotional instability, and likely insufficient access to mental health care [28,29].

Cocaine use, in particular, has been associated with increased suicidality due to its acute effects on impulsivity, aggression, and affective instability [30,31]. The study further reported a disproportionate prevalence of stimulant use, especially cocaine, among suicide victims.

Cannabis use, particularly when initiated during adolescence or early adulthood, has been linked in previous research to a higher prevalence of depressive symptoms and suicidal ideation [32,33]. In this cohort, cannabis was more frequently detected among younger males who died by hanging or falling from heights. While this observation could suggest an overlap between substance use and affective vulnerability, the absence of comprehensive psychiatric data in this study prevents establishing any causal relationship.

Chronic heroin use compromises the regulation of mood and stress response systems, contributing to emotional instability [34]. This vulnerability is often compounded by comorbid psychiatric conditions, including depression, anxiety, and personality disorders [35]. Polydrug use and elevated impulsivity further increase suicide risk. Additionally, social exclusion, unemployment, and chronic stressors contribute to the cumulative psychological burden faced by this population [36].

Psychopharmaceuticals (antidepressants, antipsychotics, benzodiazepines), were detected in several cases, either alone or in combination with substances of abuse. This co-detection may reflect non-adherence to treatment, therapeutic failure, or self-medication attempts. Notably, a subgroup of individuals with high-risk profiles, characterized by chronic alcohol use and illicit drug consumption, showed no evidence of psychiatric pharmacotherapy in hair analysis; however, this finding cannot clarify whether this reflects treatment discontinuation, non-adherence, or lack of access to care.

Conversely, another subgroup presented no toxicological evidence of recent or chronic substance use, testing negative for alcohol biomarker, illicit drugs, and psychiatric pharmacotherapy. These cases may be attributable to underlying psychiatric disorders that remained undiagnosed or untreated. Alternatively, they may reflect suicides triggered by acute psychosocial stressors, such as sudden relational breakdowns,

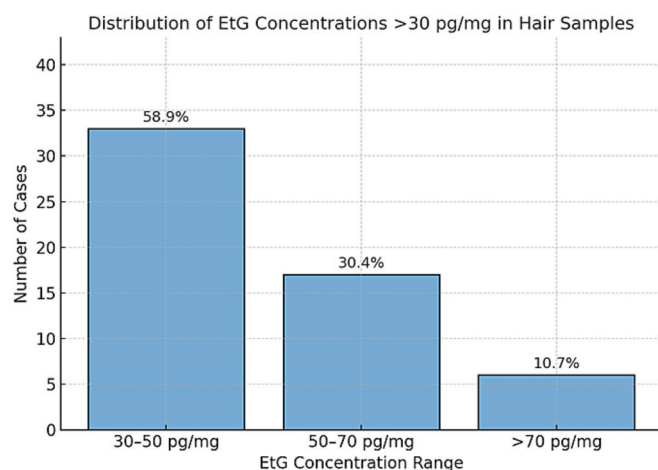


Fig. 3. Distribution of EtG concentrations > 30 pg/mg in hair samples.

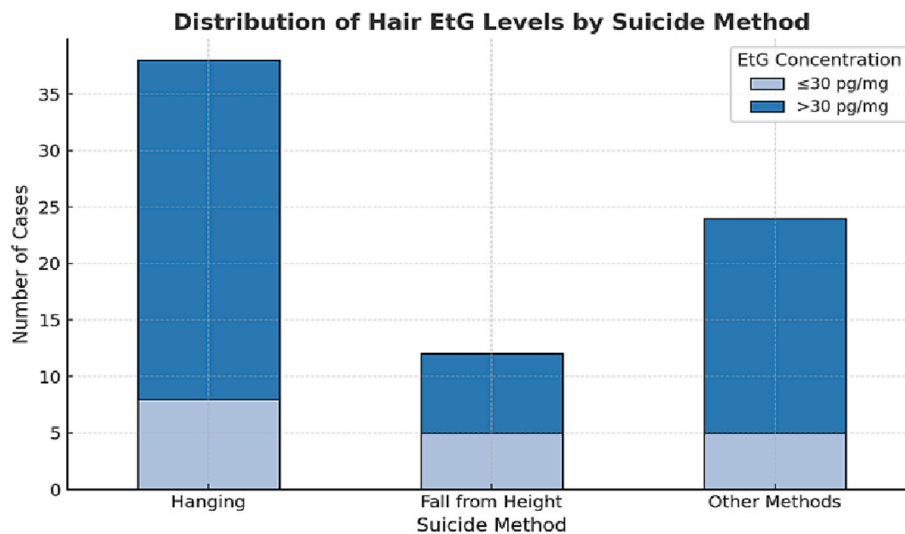


Fig. 4. Distribution of hair EtG levels by suicide method.

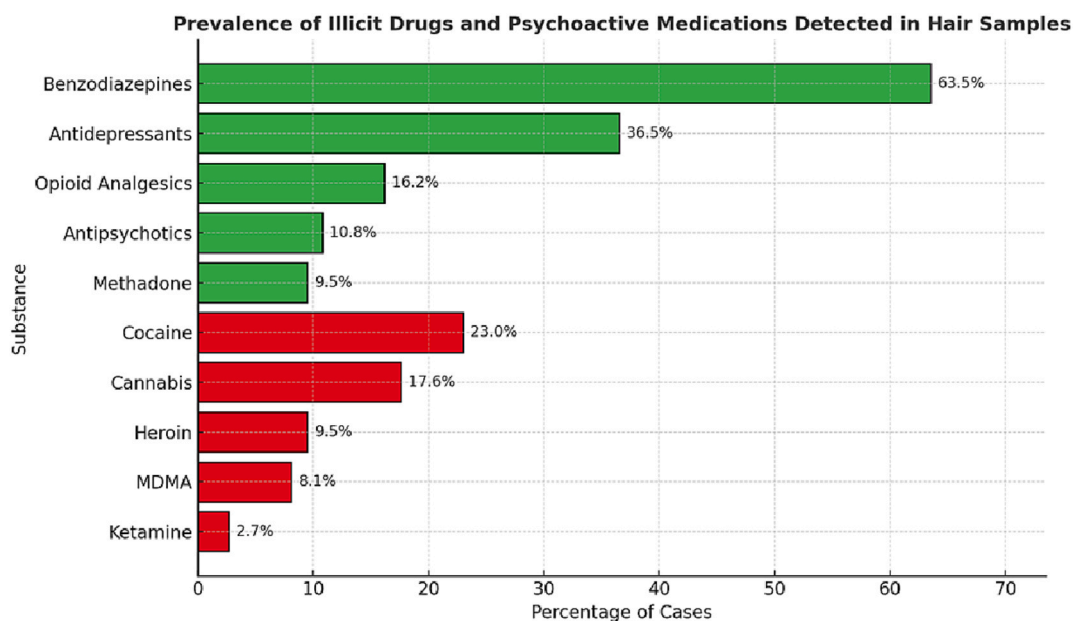


Fig. 5. Prevalence of illicit drugs and psychoactive medications detected in hair samples.

financial difficulties, legal problems, or major life events, that can precipitate suicidal crises independently of chronic substance use or diagnosable psychiatric conditions. Stratification by sex and age corroborated the observed associations. Males were more frequently involved in suicides by methods such as hanging or precipitation and showed higher prevalence of chronic excessive alcohol use and polydrug intake, particularly involving illicit substances such as cocaine, cannabis, and heroin. In contrast, females more commonly presented with detectable levels of psychopharmaceuticals, (especially antidepressants and benzodiazepines) and had a higher incidence of previous suicide attempts, suggesting more frequent contact with psychiatric care services.

Age-wise, individuals between 35 and 55 years exhibited the highest prevalence of chronic alcohol consumption and benzodiazepine detection, along with a marked use of methods such as hanging and precipitation. Notably, several cases within this age group lacked evidence of psychiatric pharmacological treatment, indicating a critical gap in mental health intervention among those with a high-risk toxicological

profile.

Overall, the findings suggest that a comprehensive perspective, which takes into account toxicological evidence together with clinical, demographic, and contextual elements, may enhance the interpretation of suicide cases and help identify areas where mental health and social support systems could be strengthened.

4.1. Limits of the study

This study is limited by the unavailability of comprehensive anamnestic data, which may result in an incomplete reconstruction of the decedents' psychiatric history and psychosocial background. Furthermore, the relatively small sample size constrains the generalizability of the findings and limits the capacity to draw definitive causal inferences. It is hoped that future research will contribute to elucidating the complex interplay between psychiatric disorders, substance abuse, and suicide risk, thereby supporting the development of more effective prevention and intervention strategies.

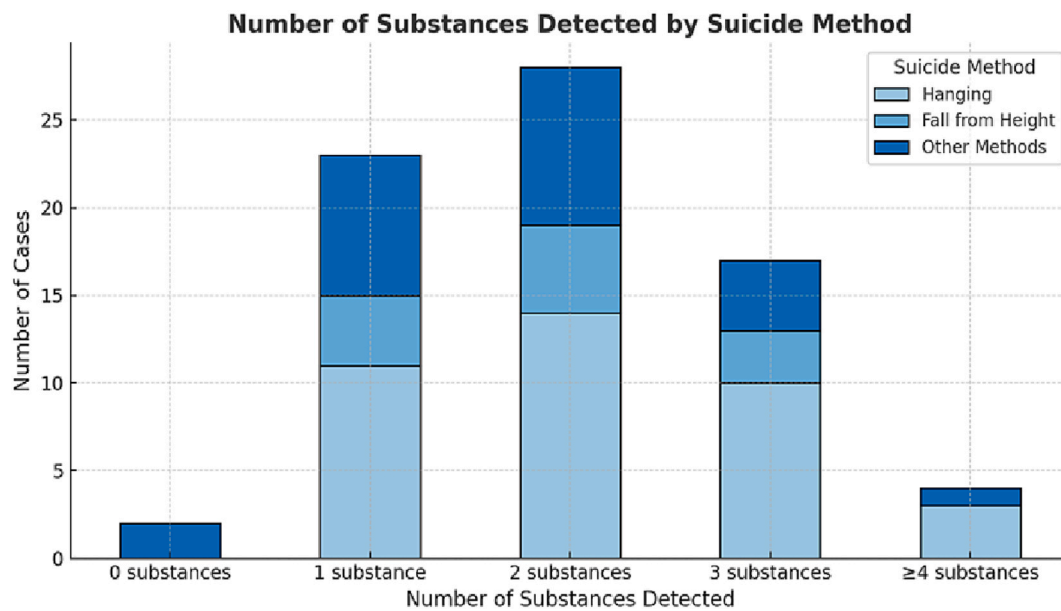


Fig. 6. Number of substances detected by suicide method.

5. Conclusion

This study delineates a multifactorial profile of suicide risk, prominently featuring chronic alcohol consumption, poly substance use, and a marked preference for specific suicide methods, particularly hanging. The retrospective toxicological analysis was instrumental in reconstructing pre-mortem behavioral patterns and elucidating substance abuse that may not have been clinically documented, thereby providing valuable insights into individual vulnerability factors contributing to suicidal behavior. The findings underscore the necessity of targeted interventions, especially for individuals with complex clinical and toxicological profiles. Comprehensive suicide prevention efforts should include systematic toxicological screening (e.g., hair EtG and drug analysis) within psychiatric and addiction services, early identification of polydrug use, and structured referral pathways to mental health care. Additionally, implementing forensic training programs for medical examiners and improving data integration between toxicology and mental health systems could enhance both prevention and post-mortem risk assessment.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used ChatGPT (OpenAI) to support the organization of the text and to improve clarity, fluency, and conciseness. After using this tool, the authors critically reviewed and edited the content as necessary and take full responsibility for the final version of the published article.

Author contributions

L.T. and C.G. contributed to conceptualization, data curation, and drafting of the original manuscript. A.G. was responsible for formal analysis and visualization. A.R. handled methodology, investigation, and manuscript review and editing. M.L. and R.S. provided supervision, resources, and validation. K.A. contributed to review and editing. C.G. also managed project administration, funding acquisition, and overall supervision. All authors read and approved the final manuscript.

Consent to participate

N/A.

Materials and/or code availability

Not applicable. All materials and methods are fully described in the manuscript; no custom code was used or developed.

Ethics approval

This study was conducted in accordance with the ethical standards of the Declaration of Helsinki (1975, revised 1983) and was approved by the Bioethics Review Board of the University of Perugia (Protocol No. 56/2023).

Funding

No funds, grants, or other support was received.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

N/A

Availability of data and materials

The datasets generated and/or analysed during the current study are not publicly available due to restrictions imposed by judicial and ethical requirements but are available from the corresponding author on reasonable request.

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