International Journal of Legal Medicine
https://doi.org/10.1007/s00414-024-03304-1

ORIGINAL ARTICLE

Accuracy of estimating postmortem interval using the relationship between total body score and accumulated degree-days: a systematic review and meta-analysis

Sandra López-Lázaro[1] · Camila Castillo-Alonso[2]

Received: 29 March 2024 / Accepted: 29 July 2024

Abstract

Objective This study aims to evaluate the relationship between Total Body Score (TBS) and Accumulated Degree-Days (ADD) for estimating postmortem interval (PMI) using the decomposition quantification system by Megyesi et al. (Megyesi MS, Nawrocki SP, Haskell NH (2005) Using Accumulated Degree-Days to Estimate the Postmortem Interval from Decomposed Human Remains. J Forensic Sci 50:1–9. https://doi.org/10.1520/jfs2004017).

Design A systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines. The methodological quality and risk of bias were assessed using the QUADAS-2 scoring system. Statical tests, including I^2 for heterogeneity assessment and subgroup analysis comparing human and pig proxies across different decomposition stages, were performed for meta-analysis.

Results The search identified 25 studies that underwent qualitative evaluation, all of which were included for quantitative analysis. The findings indicate that the TBS formula tends to overestimate ADD with a moderate mean difference of 0.5758 overall. Specifically, in pigs, ADD is overestimated significantly (1.1128), while there is a slight underestimation in humans (-0.0038). Across decomposition stages, fresh body (0.0066) and early decomposition (0.0338) show an insignificant overestimation, whereas advanced decomposition reveals a slight underestimation (-0.3378) and skeletonization indicates a substantial overestimation (1.6583).

Conclusions The relationship between TBS and ADD demonstrates high accuracy in humans during early decomposition stages, without differences in statistical significance. However, its accuracy diminishes as decomposition progresses, potentially leading to an overestimation of PMI.

Keywords Time since death · Decomposition stages · Pig models · Forensic science · Forensic anthropology

Introduction

The postmortem interval (PMI), or the time since death, is the time between death and the discovery of the body [1]. Estimating the PMI is important for understanding the circumstances surrounding death and for contributing to the identification of human remains. The PMI can be used to (i) narrow the list of possible missing persons to whom the remains may belong [2, 3]; (ii) include or exclude suspects related to the investigation based on the time interval [2–5]; and (iii) project the state in which a body may be found in the context of a missing person search [3].

Numerous studies have investigated the rate of decomposition from a fleshed body to the skeletal remains. In forensic anthropology, the standard methods for estimating PMI are based on a morphological study of the decomposition process and its changes [6]. In 2005, Megyesi et al. [7] proposed a classification of decomposition stages based on the method proposed by Galloway et al. [8]. The system involves a sum of scores, according to the visual observation of the state of decomposition divided and characterized into four categories (fresh, early decomposition, advanced

✉ Sandra López-Lázaro
sanlopez@uchile.cl

1 Departamento de Antropología, Facultad de Ciencias Sociales, Universidad de Chile, Av. Ignacio Carrera Pinto 1045, Santiago 685033, Chile

2 Independent research, Coyhaique, Chile

Published online: 08 August 2024

decomposition and skeletonization) with stages within to describe the remains. From the fleshed body to skeletal remains, the authors independently assigned a score to the head and neck, trunk and extremities. The Total Body Score (TBS) is obtained from the sum of each of the three anatomical regions [7]. With this classification, the authors proposed that a quantitative method, already existing in scientific disciplines such as forensic botany or entomology, could be applied by forensic anthropologists. As decomposition is a sequential process with small changes, the use of qualitative categories that describe small changes would increase the statistical power of the method and the estimation of the PMI [7].

Although the process and sequence of decomposition are well-known, variations over time are affected by a wide variety of factors [9, 10]. Temperature is considered to be the factor that most affects the decomposition process [7, 11, 12]. Given the absence of methods in forensic anthropology that consider decomposition as being dependent on factors other than time, Megyesi et al. [7] proposed a relationship between TBS and temperature through the accumulated-degree day (ADD). ADD is defined as the sum of average daily temperatures for the number of days the corpse had been decomposing [13]. The daily average between maximum and minimum degree was considered as temperature data (degrees Celsius) and 0ºC was the base temperature because biological processes were significantly slowed down or even inhibited at this temperature [7, 14].

With the combination of TBS as a dependent variable and ADD as an independent variable, Megyesi et al. [7] proposed a retrospective study to calculate the PMI. Although the study was developed using qualitative results, the method allows for the possibility of reproducibility, consistency, comparability and validity [4]. Since its publication, numerous studies have used TBS and ADD to estimate PMI in different species (for example, in piglets [15], rabbits [16] and horses [17]), geographical regions (such as North America [18, 19], Europe [1, 20] and Africa [21, 22]) and environments (e.g., water [23, 24], terrestrial surfaces [16, 25], buried [26, 27] and hanging [28]). The investigation of this correlation has had mixed results: some authors have obtained positive outcomes [25, 29], while others have not shown a significant relationship between these variables [30, 31].

The present systematic review and meta-analysis aimed to assess the accuracy of estimating PMI using the relationship between TBS and ADD.

Materials and methods

Protocol

The "Preferred Reporting Items for Systematic Reviews and Meta-Analyses—PRISMA" checklists and flow diagram published by Moher et al. [32] were followed, although these do not fully fit the content of this study [33].

Literature search strategy

A systematic search was carried out for studies that used the method proposed by Megyesi et al. [7] to quantify the degree of decomposition through a TBS that allows ADD and PMI to be calculated. The SciELO, LILACS, PubMed, Scopus and Web of Science databases were used. The following formula of terms was applied, which was adapted to the rules of each database:

(TBS OR total body score OR PMI OR postmortem interval) AND (ADD OR accumulated degree-days) AND (estimation OR improved OR evaluation OR application OR comparison OR scoring).

The search was conducted on October 17, 2022. Observational studies published in scientific journals written in English or Spanish, which analyzed the decomposition of humans and/or pigs according to the TBS of Megyesi et al. [7], had a known date of death and which indicated the ADD obtained, either as an average with a known sample size or through the details of each individual that allows the average to be calculated, were included.

Once the articles were obtained and duplicates had been eliminated, a first selection was made based on the title and abstract, followed by a second selection based on the full publication. These evaluations were carried out independently by two researchers using the Rayyan application which allows blind decisions and notes between reviewers and facilitates the resolution when there is disagreement between them [34]. Finally, a manual search was performed in the bibliography and reference lists of the studies which were considered eligible.

Data extraction

The data extracted were year and journal of publication, country of origin of the sample, sample size, type of sample (human or pig model), environment (terrestrial or aquatic) and, if applicable, burial depth (on the surface or buried), TBS, the average and standard deviation of the real ADD and the calculated ADD [7]. If the calculated ADD was not specified in the study, it was obtained from the formula given by the authors. To facilitate the analysis, studies which worked with humans and pig models were treated as two independent studies and were differentiated by an a and b, respectively, in the figures.

Risk of bias in studies

The risk of bias was assessed using QUADAS-2, as suggested by the Cochrane Collaboration for Systematic Reviews [35]. All publications with values of ≥ 70% were considered to have a low risk of bias and were included.

Data analysis

Being a continuous variable, the meta-analysis worked by contrasting two measures: the reference test, which corresponded to the real ADD, and the diagnostic test, known as the calculated ADD. For this, the average and standard deviation of the ADD obtained empirically by each study at a given TBS was used and compared with the ADD and standard deviation calculated using the formula of Megyesi et al. [7] for the same TBS.

Due to the high variability present between the included studies (given the diversity of study subjects, geographical and climatic differences, possible distinctions in burial methods and treatment of corpses), the meta-analysis carried out used a random effects model based on the study of DerSimonian & Laird [36] which takes both within and between study variances into account [37, 38]. The type of effect size used, which quantifies the magnitude and direction of the effect if interest, was a standardized mean difference; in this case, a positive value shows that the overall mean of the calculated ADD is higher than the real ADD, whereas a negative value indicates that the calculated ADD is lower than the real ADD. This was interpreted by Cohen [39] who suggested the classifications of small (d = 0–0.2), medium (d = 0.21–0.5), large (d = 0.51–0.8) and very large (d => 0.8) [40]; this information was plotted on a forest plot.

Heterogeneity between studies was estimated using the I^2 test. A value of 0% indicates no observed heterogeneity, with 25% indicating low heterogeneity, 50% moderate heterogeneity and 75% high heterogeneity [41]. A moderator analysis was performed for remains which were buried or on the surface, in aquatic or terrestrial environments, human or pig models and TBS values. To detect publication bias, Egger's method [42] was applied and a funnel plot was obtained.

In addition, meta-analyses were performed to examine the results between subgroups: outcomes were compared between pig vs. human models, as well as between the decomposition stages described by Megyesi et al. [7]; fresh body (TBS = 3), early decomposition (TBS = 4–6), advanced decomposition (TBS = 17–24) and skeletonization (TBS = 25–35). For the latter, the average of the general ADD was not necessarily used, but different averages were calculated if possible, grouping the individuals according to the TBS observed in each group; this included cases of the same individual in different stages of decomposition. All statistical tests, graphs and figures were performed using R (version 4.2.1; R Core Team, 2022) and the 'metafor' package version 3.8.1 [43].

Results

Study selection

The search of the five databases identified 1228 articles, with 1081 remaining after the removal of duplicates. The review of the title and abstract reduced this number to 43 and the reading of full publications decreased it further to 21. Finally, the manual search resulted in the addition of 4, leaving a total of 25 articles for analysis (Fig. 1). As there were two publications that worked with human individuals and pigs, the statical analysis was carried out as if there were 27 articles.

Table 1 summarizes the general characteristics of the studies. These were carried out with populations from the United States of America (N = 9), South Africa (N = 5), Australia (N = 3), the United Kingdom (N = 2), Sweden (N = 2), the Netherlands (N = 1), China (N = 1), Italy (N = 1) and Serbia (N = 1). Overall, 24 of the 25 articles were published in specialized forensic science or legal medicine research journals, both locally and internationally. The total number of participants was 751 (542 humans and 209 pigs).

Risk of bias in studies

The results of QUADAS-2 showed a low risk of bias and, hence, a high methodological quality (Table 2). Two questions in the tool were considered not applicable: Question 5 (about the index test) asked about the use of a threshold to define the index test, which does not apply to these variables, while Question 8 (about flow and timing) asked about the time interval for the analysis, which was not considered because index test (calculated ADD) and reference standard (real ADD) were compared over the same time period [44].

Outcomes and meta-analyses

General results

The results of the meta-analysis showed an overall mean difference of 0.5758 (p = 0.0141; SE = 0.2345; 95% CI = 0.1162–1.0354), which indicates that the value obtained

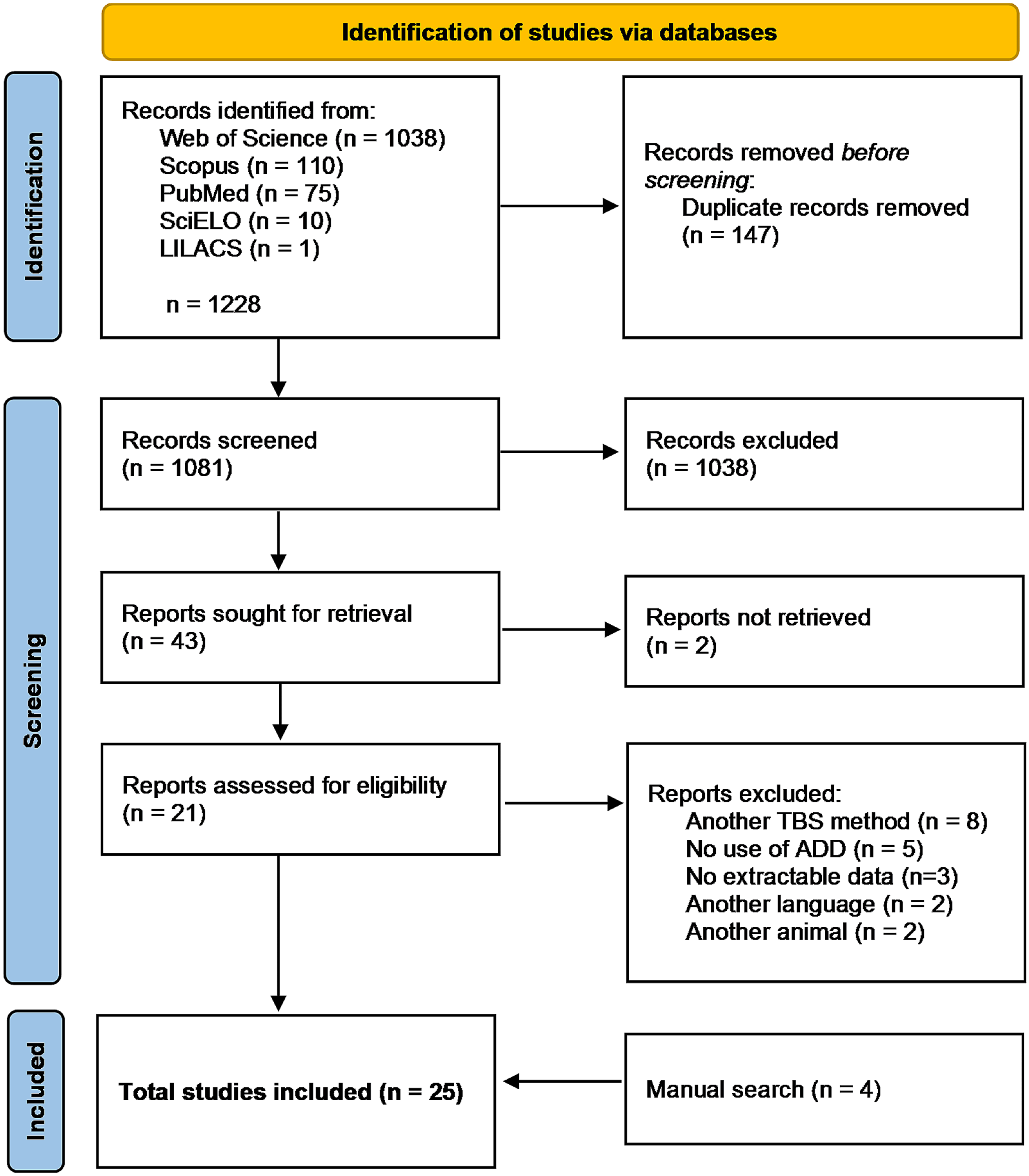

Fig. 1 Flow diagram describing the process of the systematic review, following the guidelines proposed by PRISMA

Table 1 Main characteristics of eligible studies

Author, year		Country	Journal	*N*	H/*P*
1.	Megyesi et al., 2005	USA	Journal of Forensic Science	68	H
2.	Cross & Simmons, 2010	UK	Journal of Forensic Science	34	P
3.	Heaton et al., 2010	UK	Journal of Forensic Science	187	H
4.	Parks, 2011	USA	Journal of Forensic Science	1	H
5.	Spicka et al., 2011	USA	Forensic Science International	12	P
6.	Meyer et al., 2013	USA	Journal of Forensic Science	6	P
7.	Myburgh et al., 2013	South Africa	Forensic Science International	16	P
8.	Sutherland et al., 2013	South Africa	Forensic Science International	30	P
9.	Roberts & Dabbs, 2015	USA	Journal of Forensic Science	8	P
10.	Marhoff et al., 2016	Australia	Australian of Forensic Sciences	2	P
11.	Suckling et al., 2016	USA	Journal of Forensic Science	10	H
12.	Wang et al., 2017	China	Forensic Science International	1/4	H/P
13.	Bugelli et al., 2018	Italy	Forensic Sciences Research	2	H
14.	Ceciliason et al., 2018	Sweden	Forensic Science International	140	H
15.	Connor et al., 2018	USA	Journal of Forensic Science	17/22	H/P
16.	Marais-Werner et al., 2018	South Africa	International Journal of Legal medicine	25	P
17.	Marhoff-Beard et al., 2018	Australia	Forensic Science International	16	P
18.	Tomić et al., 2018	Serbia	Romanian Journal of Legal Medicine	2	P
19.	Finaughty & Morris, 2019	South Africa	Forensic Science International	16	P
20.	Forbes et al., 2019	South Africa	Forensic Science International	16	P
21.	Baigent et al., 2020	USA	Forensic Science International	26	H
22.	Giles et al., 2020	USA	Forensic Science International	26	H
23.	Pittner et al., 2020	Netherlands	PloS One	2	H
24.	Wilson et al., 2020	Australia	Forensic Science International	1	H
25.	Alfsdotter & Petaros, 2021	Sweden	Journal of Forensic Science	82	H

H, human; p, pig.

from the calculation proposed by Megyesi et al. [7] was higher than the real ADD (Fig. 2). According to Cohen's interpretation [39], this mean difference was medium, which means that the estimation formula's predictions have a moderate but noticeable difference from the actual ADD.

The I^2 value was 92.40% ($p < 0.0001$), implying high heterogeneity. The evaluation of moderators showed that only the use of humans (k = 13) or pigs (k = 14) ($p = 0.0271$) and TBS value ($p = 0.0015$) presented statistical significance. In the case of environment, where the categories were terrestrial (k = 27), aquatic (k = 1) or both (k = 1) ($p = 0.5142$), and of burial depth, where the categories were surface (k = 23), buried (k = 3), on the surface or in a sewer (k = 1), there was no statistical significance ($p = 0.3267$).

Egger's test shows hints of possible publication bias ($p = 0.0049$) which is also seen in the funnel plot (Fig. 3).

Results for human versus pig

Human Thirteen papers reviewed decomposition in the human body and were analyzed further. The results of the meta-analysis showed a mean difference of -0.0038 ($p = 0.9891$; SE = 0.2792; 95% CI=-0.5511–0.5435) where the values of calculated ADD were lower on average than the real ADD (Fig. 2). The mean difference was small and statistically insignificant; therefore, the Megyesi's formula [7] has a reasonably accurate estimate of ADD when used on humans. The I^2 value was 91.89% ($p < 0.0001$), showing high heterogeneity. Egger's test shows no indication of publication bias ($p = 0.2440$).

Pig Fourteen papers reviewed decomposition in pig bodies and were analyzed further. The results of the meta-analysis showed a mean difference of 1.1128 ($p = 0.0050$; SE = 0.3961; 95% CI = 0.3363–1.8892) which indicates that the calculated ADD values were higher on average than real ADD (Fig. 2). The mean difference is very large and statistically significant; hence, this discrepancy suggests that this formula lacks sufficient precision to provide reliable data when used in pigs. The I^2 value was 90.42% ($p < 0.0001$), indicating high heterogeneity. Egger's test does not show signs of publication bias ($p = 0.0640$).

Results for decomposition stage

Fresh body Six publications with 49 observations (29 humans and 20 pigs) were analyzed. The results of the meta-analysis showed a mean difference of 0.0066 ($p = 0.9740$; SE = 0.2020; CI 95%=-0.3894 to 0.4026) (Fig. 4) where calculated ADD values were higher than real ADD values

Table 2 Risk of bias assessed for each study using the QUADAS-2 tool

Author, year	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	% yes
Megyesi et al., 2005	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Cross & Simmons, 2010	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Heaton et al., 2010	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Parks, 2011	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Spicka et al., 2011	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Meyer et al., 2013	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Myburgh et al., 2013	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Sutherland et al., 2013	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Roberts & Dabbs, 2015	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Marhoff et al., 2016	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Suckling et al., 2016	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Wang et al., 2017	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Bugelli et al., 2018	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Ceciliason et al., 2018	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Connor et al., 2018	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Marais-Werner et al., 2018	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Marhoff-Beard et al., 2018	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Tomić et al., 2018	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Wescott et al., 2018	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Finaughty & Morris, 2019	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Forbes et al., 2019	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Baigent et al., 2020	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Giles et al., 2020	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Pittner et al., 2020	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Wilson et al., 2020	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100
Alfsdotter & Petaros, 2021	✓	✓	✓	✓	-	✓	✓	-	✓	✓	100

Q1) Was a consecutive or random sample of patients enrolled? Q2) Was a case control design avoided? Q3) Did the study avoid inappropriate exclusions? Q4) Were the index test results interpreted without knowledge of the results of the reference standard? Q5) If a threshold was used, was it pre-specified? Q6) Is the reference standard likely to correctly classify the target condition? Q7) Were the reference standard results interpreted without knowledge of the results of the index test? Q8) Was there an appropriate interval between index test and reference standard? Q9) Did all of the patients receive the same reference standard? Q10) Were all patients included in the analysis? √: yes; X: no; -: not applicable.

on average. The mean difference was small and statistically insignificant, which means that the results of the calculated ADD are statistically indistinguishable from real ADD in the fresh body stage. The I^2 value was 0% ($p=1.0$), indicating no heterogeneity. Egger's test shows no evidence of publication bias ($p=0.7437$).

Early decomposition There were 16 publications with 416 observations (321 humans and 95 pigs) which were analyzed. The results of the meta-analysis showed a mean difference of 0.0338 ($p=0.6271$; SE = 0.0695; 95% CI=-0.1025 to 0.1700), that is, the calculated ADD values were higher on average than the real ADD values (Fig. 4). The mean difference is small and statistically insignificant; therefore, the formula can be considerable reliable for estimating ADD in the early decomposition stage. The I^2 value was 0% ($p=0.9116$), indicating no heterogeneity. Egger's test shows no evidence of publication bias ($p=0.2008$).

Advance decomposition There were 19 publications with 542 observations (416 humans and 126 pigs) analyzed. The results of the meta-analysis showed a mean difference of -0.3378 ($p=0.1239$; SE = 0.2195; 95% CI=-0.7680 to 0.0925) (Fig. 4) where the value of calculated ADD is lower on average than the value of real ADD. The mean difference was medium but statistically insignificant; thus, the formula has a noticeable difference from real ADD, potentially due to random variability. The I^2 value was 87.55% ($p<0.0001$), implying high heterogeneity. Egger's test does not show signs of publication bias ($p=0.0976$).

Skeletonization Seventeen publications with 370 observations (251 humans and 119 pigs) were analyzed. The results of the meta-analysis showed a mean difference of

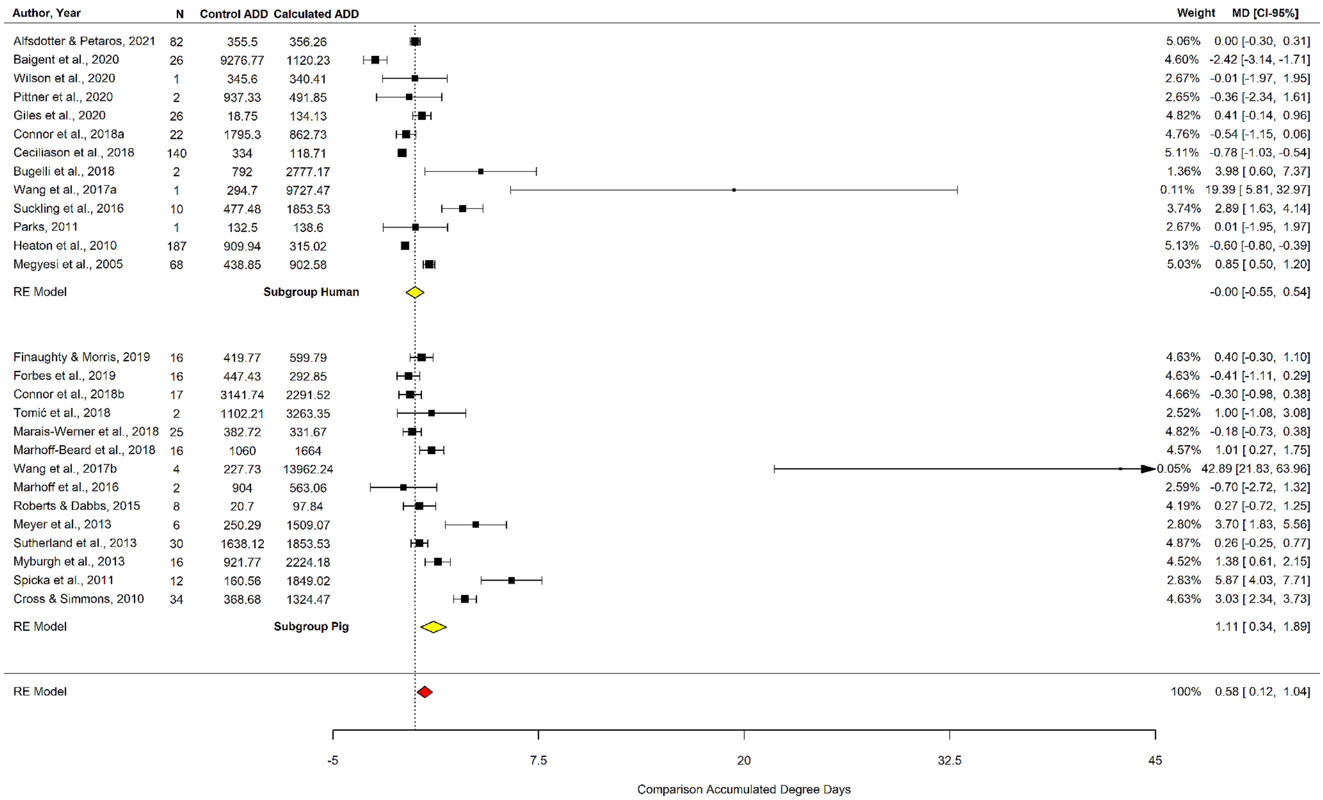

Fig. 2 Forest plot showing the mean difference between Control ADD and Calculated ADD. MD = mean difference. CI = confidence interval. The red diamond shows the result averaged in general and yellow diamonds show the result averaged for human and pig subgroups

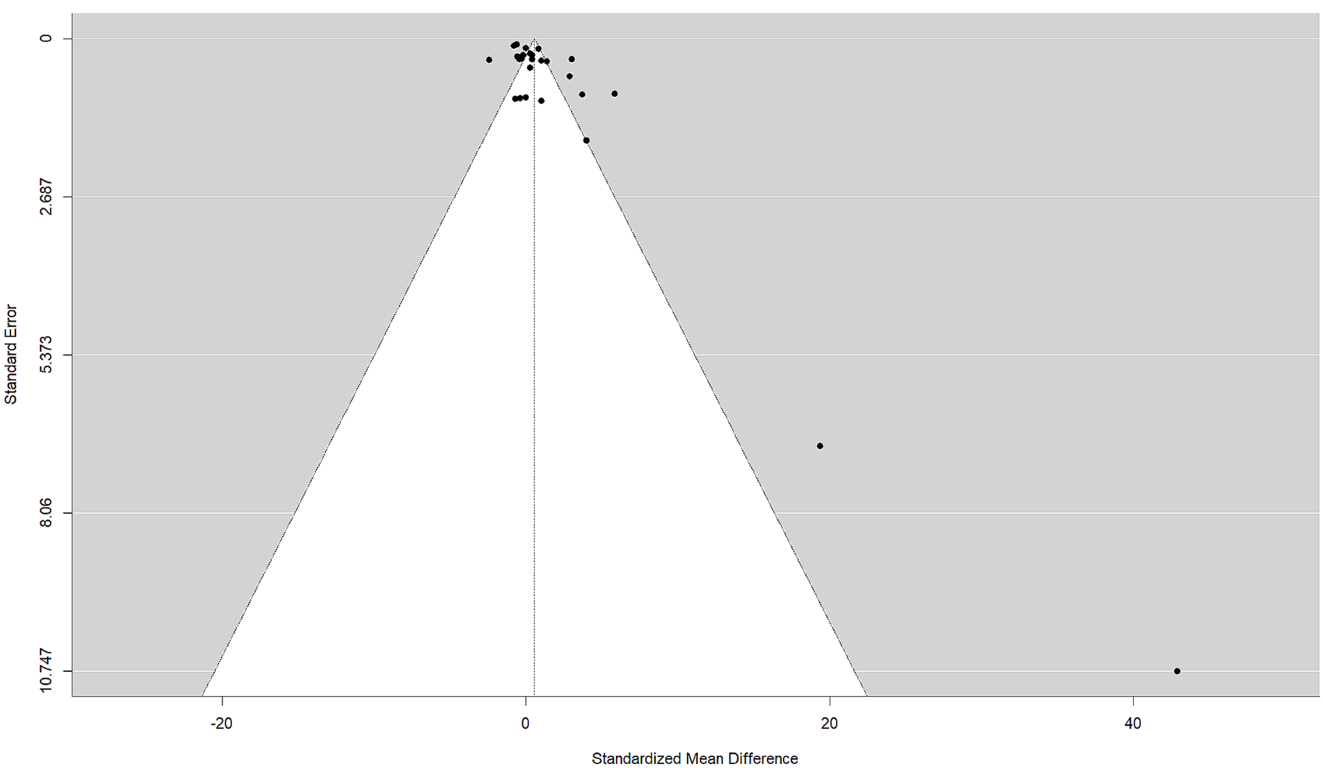

Fig. 3 Egger's funnel plot

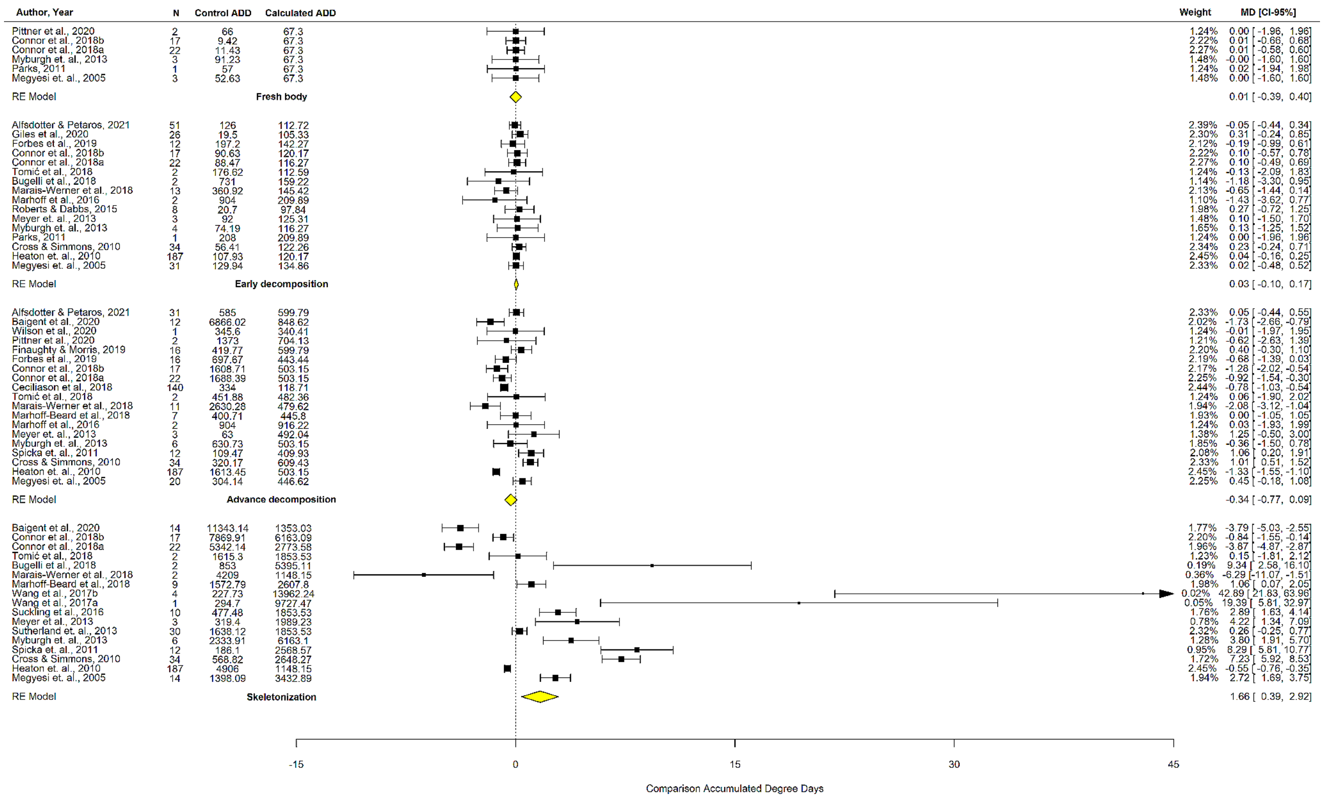

Fig. 4 Forest plot showing the mean difference between Control ADD and Calculated ADD in subgroups according to the stages of decomposition (Megyesi et al., 2005). MD = mean difference. CI = confidence interval. Yellow diamonds show the result averaged for every subgroup

Table 3 Summary of the results

		Mean difference	*p*-val	I^2	Moderator analysis	Publication bias
General results		0. 5758	0.0141	92.40%	TBS (p-val 0.0015) H/P (p-val 0.0271)	Yes
Sample	Human	-0.0038	0.9891	91.89%	-	No
	Pig	1.1128	0.0050	90.42%	-	No
TBS	Fresh body	0.0066	0.9740	0%	-	No
	Early decomposition	0.0338	0.6271	0%	-	No
	Advance decomposition	-0.3378	0.01239	87.55%	-	No
	Skeletonization	1.6583	0.0101	95.96%	-	Yes

H/P = moderator about use in human versus in pig.

1.6583 ($p = 0.0101$; SE = 0.6448; 95% CI = 0.3945–2.9221) (Fig. 4) in which the average value of calculated ADD was higher than the real ADD. This mean difference is very large and statistically significant, which suggests that the formula is not accurate for calculating ADD in the skeletonization stage.

The I^2 value was 95.96% ($p < 0.0001$), showing high heterogeneity. Egger's test, while not significant, suggests a trend toward publication bias ($p = 0.0574$).

Summary of meta-analysis results

Table 3 summarizes the results. The general study of the mean difference, considering humans and pigs without differentiation by TBS, showed a medium magnitude of difference where the value of ADD is overestimated when using the formula of Megyesi et al. [7]. The results by type of sample indicated that this overestimation is also present in analysis when using pigs, with a very large magnitude of difference, whereas its use to estimate ADD in humans has a minimal underestimation with no statical significance. By decomposition stage, its use in fresh body and early decomposition stages results in an estimated ADD value that is insignificantly overestimated; as it progresses to the advanced decomposition stage, the estimated value is slightly underestimated and the estimated ADD value in the skeletonization stage is ultimately significantly overestimated.

The heterogeneity of the results was high, except for the fresh body and early decomposition stages, where it was null. Additionally, in the overall analysis there is a clear suggestion of publication bias, which does not appear in the analysis of the reviewed subgroups, except for the skeletonization stage.

Discussion

PMI estimations primarily rely on soft tissue degradation [45], influenced by key abiotic factors: temperature, moisture, pH and the partial pressure of oxygen [46], with the first one being the principal variable influencing the velocity and rate of decomposition [11]. According to Megyesi et al., over 80% of the observed variation in human decomposition can be explained by elapsed time and temperature [7]. The ADD metric is derived from this relationship, standardizing the accumulated temperature over time and allowing its application in PMI estimation [46], in addition to enabling comparison between different methods and studies that use it. With the aim of standardizing decomposition for use in PMI calculations, Megyesi and colleagues developed their TBS, which quantifies the sequential process of soft tissue degradation independently of other processes and places an emphasis on the relationship between time and temperature through ADD [7].

Based on the stages described qualitatively from cases in various climates, clothing states and completeness, and recognizing that decomposition follows a semi-continuous and predictable pattern [45], a quantitative points value system was proposed for widespread forensic application. This method, based on TBS and ADD, has been widely criticized; however, it has continued to be used without modification by researchers [47]. Criticisms focus possible variations by microhabitat between body discovery sites and weather stations locations, affecting temperature measurement precision [48, 49], or relying on photographs rather than direct observation [47]. In addition, despite high replicability in its use in humans [50], observers experience influence assessments using digital images [51]. The major criticism targets its intended worldwide application, as methods that use ADD may not account for sufficient geoclimatic variation to correctly record the decay rates in different regions [21, 52].

This study initially analyzed the relationship between ADD and TBS in general, without differentiating by burial status, environments (terrestrial or aquatic), species (human or pig) or degree of decomposition. The results indicate that the effect of ADD on TBS overestimates the PMI according to the formula of Megyesi et al. [7]. This overestimation can be attributed to the challenges of generating a universal mathematical model from a dependent variable based on numerous small observable changes [53] and errors in understanding the linear regression statistical model, as noted in previous studies [5, 54]. Despite this, the method of Megyesi et al. continues to be used without modification [47].

It is important to consider the high heterogeneity in the results, which limits their interpretation. This study aimed to find variables that explain this heterogeneity. While some variables provided further insights about the accuracy of the TBS and ADD relationship to estimate PMI, it was not possible to fully clarify it. Possible reasons include differences in habitats not analyzed in this study, significant variations in the real ADD results based on the same TBS within the same studies due to the difficulties in accurately measuring temperature differences between nearby places [48, 55] or the grouping of individuals with very dissimilar characteristics, as seen in Tomić et al. [20], where the average was generated from two pig cases at different depths, one on the surface and the other in a sewer hole.

Another pertinent aspect to consider is publication bias. The overall analysis reveals a clear presence of publication bias, attributed to selective reporting favoring studies with positive results over those with non-significant results or findings deemed less relevant [56]. Additionally, there is a linguistic and geographical bias, wherein studies published in languages other than English or in non-indexed national journals are less likely to be included in meta-analyses [57].

Interestingly, this publication bias is absent in the subgroup analyses. This discrepancy could be explained by heterogeneity, as the subgroups may comprise more homogeneous studies, thereby reducing heterogeneity and diminishing the impact of publication bias [58], as seen in fresh body and early decomposition stage results. Additionally, in the overall analysis, a few large or influential studies with significant results may drive the suggestion of publication bias [42]. In subgroup analyses, these influential studies could be less prominent or excluded, as seen in the advanced decomposition stage. However, skeletonization, which shows a tendency towards publication bias, aligns more closely with the overall results and does not meet these conditions.

Regarding the reviewed variables, most experimental studies analyzed samples located on the surface. However, some observed differences in buried samples. Pittner et al. [26] found that morphological characterization tables were adequate but noted a significant temporal difference, with TBS underestimating the ADD for burial intervals. Marais-Werner et al. [27] compared decomposition processes and found a similar pattern for buried and aboveground pigs, although buried pigs decayed 55.2–88.9% slower. These temporal differences suggest that corrections or recalculations are necessary for future research [26]. In this study, no significant differences were found between surface and buried decomposition processes. However, the validity of these findings is limited due to the small number of studies and their sample sizes.

This was repeated in PMI comparisons in territorial and aquatic settings. Heaton et al. [23] found a significant correlation between ADD and decomposition across various study locations. In contrast, Alfsdotter & Petaros [24] demonstrated that while surface decomposition correlated with ADD after formula adjustments, this relationship performed poorly in aquatic environments, possibly due to additional decomposition factors. The present meta-analysis found no significant differences, yet the limited number of studies and small sample sizes restrict the validity of the findings. This may be linked to the previously observed publication bias and suggests a lack of published studies that provide detailed insights into the variables and their specific influences on the relationship between TBS, ADD and PMI.

The results from human samples indicate a slight underestimation, suggesting that the method of Megyesi et al. [7], although minimal, underestimates PMI based on TBS and ADD. However, the results exhibit high heterogeneity. Various authors comparing their findings with the proposed method report a strong correlation, yet also note instances of significant PMI overestimation, where their samples reached ADD in a shorter time [28, 59], as well as an underestimation when more time was required [26, 60]. In contrast, a meta-analysis of studies using pigs shows PMI overestimation, also with notable heterogeneity. Comparisons using the method of Megyesi et al. [7] indicate a PMI overestimation in some studies [61], while others highlight a consistent underestimation [52, 62].

The subgroups based on decomposition stage exhibit low heterogeneity for the fresh body and early decomposition stages, but high heterogeneity for advanced decomposition and skeletonization. This translates to the first two presenting estimated values of ADD which are indistinguishable from the actual ADD value, whereas the latter two exhibit moderate underestimation in advanced decomposition and very significant overestimation in skeletonization. Thus, as TBS increases, so does the error of the formula for calculated ADD, leading to greater discrepancies in PMI estimates across various studies.

This aligns with a recognized limitation: estimating time since death becomes more complex with time and tissue decomposition progression [63–65]. Myburgh et al. observed a linear decay rate initially, which becomes more variable at higher TBS values [21]. Similarly, Suckling et al. noted reduced prediction accuracy in advanced decomposition and skeletonization stages [59], while Wescott et al. reported increased standard deviation in ADD over time [31].

Conclusions

It was concluded from the statistical analysis carried out in the present investigation that the method to estimate PMI, based on the relationship between TBS and ADD, exhibits high accuracy in humans during early decomposition stages. However, its accuracy deteriorates as decomposition progresses, leading to overestimation. This indicates that the method is not optimal as a universal formula and tends to underestimate PMI in human models while overestimating it in pig models. Limitations of this study include high observed heterogeneity and dissimilar results between studies.

Regarding decomposition stages, the method showed the highest accuracy in estimating PMI for the fresh body and early decomposition stages. In contrast, advanced decomposition and skeletonization stages demonstrated increased estimation errors as the degree of soft tissue degradation increased.

While the relationship between TBS, ADD and PMI proposed by the authors represents a significant contribution to forensic sciences, its application in different geoclimatic contexts necessitates adaptation and modification.

Author contributions Conceptualization: Sandra López-Lázaro, Camila Castillo-Alonso; Methodology: Sandra López-Lázaro, Camila Castillo-Alonso; Formal analysis and investigation: Sandra López-Lázaro, Camila Castillo-Alonso; Writing - original draft preparation: Sandra López-Lázaro, Camila Castillo-Alonso; Writing - review and editing: Sandra López-Lázaro, Camila Castillo-Alonso; Funding acquisition: Sandra López-Lázaro; Resources: Sandra López-Lázaro; Supervision: Sandra López-Lázaro, Camila Castillo-Alonso.

Funding This research was supported by the Agencia Nacional de Investigación y Desarrollo (ANID) of Chile, through the project ANID FONDECYT 1211534.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Declarations 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.

Competing interests The authors declare no competing interests.

References

1. Gelderman HT, Boer L, Naujocks T et al (2018) The development of a post-mortem interval estimation for human remains found on land in the Netherlands. Int J Legal Med 132:863–873. https://doi.org/10.1007/s00414-017-1700-9
2. Larkin B, Iaschi S, Dadour I, Tay GK (2010) Using accumulated degree-days to estimate postmortem interval from the DNA yield of porcine skeletal muscle. Forensic Sci Med Pathol 6:83–92. https://doi.org/10.1007/s12024-009-9109-5
3. Simmons T (2017) Post-mortem interval estimation: an overview of techniques. In: Taphonomy of Human Remains: Forensic Analysis of the Dead and the Depositional Environment: Forensic Analysis of the Dead and the Depositional Environment. pp 134–142
4. Keough N, Myburgh J, Steyn M (2017) Scoring of decomposition: a proposed amendment to the Method when using a Pig Model for Human studies. J Forensic Sci 62:986–993. https://doi.org/10.1111/1556-4029.13390
5. Moffatt C, Simmons T, Lynch-Aird J (2016) An Improved equation for TBS and ADD: establishing a Reliable Postmortem interval Framework for Casework and Experimental studies. J Forensic Sci 61:201–207. https://doi.org/10.1111/1556-4029.12931
6. Connor M, Baigent C, Hansen ES (2019) Measuring Desiccation using qualitative changes: a step toward determining Regional decomposition sequences. J Forensic Sci 64:1004–1011. https://doi.org/10.1111/1556-4029.14003
7. Megyesi MS, Nawrocki SP, Haskell NH (2005) Using accumulated degree-days to Estimate the Postmortem interval from decomposed human remains. J Forensic Sci 50:1–9. https://doi.org/10.1520/jfs2004017
8. Galloway A, Birkby WH, Jones AM et al (1989) Decay rates of human remains in an arid environment. J Forensic Sci 34:607–616. https://doi.org/10.1520/JFS12680J
9. Gelderman HT, Kruiver CA, Oostra RJ et al (2019) Estimation of the postmortem interval based on the human decomposition process. J Forensic Leg Med 61:122–127. https://doi.org/10.1016/j.jflm.2018.12.004
10. İşcan MY, Steyn M (2013) The Human Skeleton in Forensic Medicine, 3rd editio. Charles C Thomas, Springfield
11. Campobasso C, Di Pietro G, Introna F (2001) Factors affecting decomposition and Diptera colonization. Forensic Sci Int 120:18–27. https://doi.org/10.1016/S0379-0738(01)00411-X
12. Mann RW, Bass WM, Meadows L (1990) Time since death and decomposition of the human body: variables and observations in case and experimental field studies. J Forensic Sci 35:103–111. https://doi.org/10.1520/JFS12806J
13. Vass A, Bass W, Wolt J et al (1992) Time since Death determinations of human cadavers using soil solution. J Forensic Sci 37:1236–1253
14. Clarke A, Morris GJ, Fonseca F et al (2013) A low temperature limit for life on Earth. PLoS ONE 8:e66207. https://doi.org/10.1371/journal.pone.0066207
15. Sutherland A, Myburgh J, Steyn M, Becker PJ (2013) The effect of body size on the rate of decomposition in a temperate region of South Africa. Forensic Sci Int 231:257–262. https://doi.org/10.1016/j.forsciint.2013.05.035
16. Wang Y, Ma M, yun, Jiang X, yu et al (2017) Insect succession on remains of human and animals in Shenzhen, China. Forensic Sci Int 271:75–86. https://doi.org/10.1016/j.forsciint.2016.12.032
17. Nasti A (2019) Accumulated degree days (add) and sequence of Disarticulation in the Reconstruction of Postmortem Interval (pmi). A contribution to forensic taphonomy. Rev Argentina Antropol Biol 21:1–10. https://doi.org/10.17139/raab.2019.0021.01.07
18. Roberts LG, Dabbs GR (2015) A taphonomic study exploring the differences in Decomposition Rate and Manner between Frozen and Never Frozen Domestic pigs (Sus scrofa). J Forensic Sci 60:588–594. https://doi.org/10.1111/1556-4029.12717
19. Giles SB, Harrison K, Errickson D, Márquez-Grant N (2020) The effect of seasonality on the application of accumulated degree-days to estimate the early post-mortem interval. Forensic Sci Int 315. https://doi.org/10.1016/j.forsciint.2020.110419
20. Tomić Z, Stojanac N, Kovačević Z et al (2018) Scoring and comparing decomposition of pig carcass in a sewer manhole and on the soil surface. Rom J Leg Med 26:162–166. https://doi.org/10.4323/rjlm.2018.162
21. Myburgh J, L'Abbé EN, Steyn M, Becker PJ (2013) Estimating the postmortem interval (PMI) using accumulated degree-days (ADD) in a temperate region of South Africa. Forensic Sci Int 229. https://doi.org/10.1016/j.forsciint.2013.03.037. :165.e1-165.e6
22. Finaughty DA, Morris AG (2019) Precocious natural mummification in a temperate climate (Western Cape, South Africa). Forensic Sci Int 303:109948. https://doi.org/10.1016/j.forsciint.2019.109948
23. Heaton V, Lagden A, Moffatt C, Simmons T (2010) Predicting the postmortem submersion interval for human remains recovered from U.K. waterways. J Forensic Sci 55:302–307. https://doi.org/10.1111/j.1556-4029.2009.01291.x
24. Alfsdotter C, Petaros A (2021) Outdoor human decomposition in Sweden: a retrospective quantitative study of forensic-taphonomic changes and postmortem interval in terrestrial and aquatic settings. J Forensic Sci 66:1348–1363. https://doi.org/10.1111/1556-4029.14719
25. Parks CL (2011) A study of the human decomposition sequence in Central Texas. J Forensic Sci 56:19–22. https://doi.org/10.1111/j.1556-4029.2010.01544.x
26. Pittner S, Bugelli V, Eric Benbow M et al (2020) The applicability of forensic time since death estimation methods for buried bodies in advanced decomposition stages. PLoS ONE 15:1–26. https://doi.org/10.1371/journal.pone.0243395
27. Marais-Werner A, Myburgh J, Becker PJ, Steyn M (2018) A comparison between decomposition rates of buried and surface remains in a temperate region of South Africa. Int J Legal Med 132:301–309. https://doi.org/10.1007/s00414-017-1618-2
28. Bugelli V, Gherardi M, Focardi M et al (2018) Decomposition pattern and insect colonization in two cases of suicide by hanging. Forensic Sci Res 3:94–102. https://doi.org/10.1080/20961790.2017.1418622
29. Wilson A, Neilsen P, Berry R et al (2020) Quantifying human post-mortem movement resultant from decomposition processes. Forensic Sci Int Synerg 2:248–261. https://doi.org/10.1016/j.fsisyn.2020.07.003
30. Franceschetti L, Pradelli J, Tuccia F et al (2021) Comparison of accumulated degree-days and entomological approaches in post mortem interval estimation. Insects 12:1–11. https://doi.org/10.3390/insects12030264
31. Wescott D, Steadman D, Miller N et al (2018) Validation of the total body Score/Accumulated degree-day model at three human decomposition facilities. Forensic Anthropol 1:143–149. https://doi.org/10.5744/fa.2018.0015
32. Moher D, Liberati A, Tetzlaff J, Altman DG (2010) Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Int J Surg 8:336–341. https://doi.org/10.1016/j.ijsu.2010.02.007
33. Page MJ, Moher D, Bossuyt PM et al (2021) PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews. Br Med J 372:1–36. https://doi.org/10.1136/bmj.n160

34. Ouzzani M, Hammady H, Fedoriwicz Z, Elmagarmid A (2016) Rayyan QCRI. Systematic reviews
35. Whiting PF, Rutjes AWSS, Sterne JAC et al (2011) QUADAS-2: a revised tool for the quality assessment of diagnostic accuracy studies. Ann Intern Med 155:529–536
36. DerSimonian R, Laird N (1986) Meta-analysis in clinical trials. Control Clin Trials 7:177–188. https://doi.org/10.1016/0197-2456(86)90046-2
37. Nikolakopoulou A, Mavridis D, Salanti G (2014) How to interpret meta-analysis models: fixed effect and random effects meta-analyses. Evid Based Ment Health 17:64. https://doi.org/10.1136/eb-2014-101794
38. Higgins J, Thompson S, Deeks J, Altman D (2003) Measuring inconsistency in meta-analyses. BMJ (Education Debate) 327:557–560. https://doi.org/10.1007/s10844-006-2974-4
39. Cohen J (2013) Statistical Power Analysis for the behavioral sciences. Stat Power Anal Behav Sci. https://doi.org/10.4324/9780203771587
40. Morgan GA, Leech NL, Gloeckner GW, Barrett KC (2004) SPSS for introductory statistics: Use and interpretation, 2nd editio. Psychology Press
41. Khoshdel AR, Attia J, Carney SL (2006) Basic concepts in meta-analysis: a primer for clinicians. Int J Clin Pract 60:1287–1294. https://doi.org/10.1111/j.1742-1241.2006.01078.x
42. Egger M, Smith GD, Schneider M, Minder C (1997) Bias in meta-analysis detected by a simple, graphical test. BMJ Br Med J 315:629. https://doi.org/10.1136/BMJ.315.7109.629
43. Viechtbauer W (2010) Conducting meta-analyses in R with the metafor package. J Stat Softw 36:1–48. https://doi.org/10.18637/jss.v036.i03
44. Ciapponi A (2015) QUADAS-2 : instrumento para la evaluación de la calidad de estudios de precisión diagnóstica QUADAS-2 : an instrument for the evaluation of the quality of diagnostic precision studies. Evidencia 18:22–26
45. Troutman L, Moffatt C, Simmons T (2014) A preliminary examination of differential decomposition patterns in mass graves. J Forensic Sci 59:621–626. https://doi.org/10.1111/1556-4029.12388
46. Vass AA (2011) The elusive universal post-mortem interval formula. Forensic Sci Int 204:34–40. https://doi.org/10.1016/j.forsciint.2010.04.052
47. Hayman J, Oxenham M (2020) The development of grading systems to determine human decomposition. Estimation of the Time since Death: Current Research and Future trends. Elsevier Inc., pp 229–249
48. Catts EP (1992) Problem in estimating the postmortem interval in death investigations. J Agric Entomol 9:245–255
49. Archer MS (2004) The Effect of Time after Body Discovery on the Accuracy of Retrospective Weather Station Ambient Temperature corrections in Forensic Entomology. J Forensic Sci 49:JFS2003258–JFS2003257. https://doi.org/10.1520/JFS2003258
50. Dabbs GR, Connor M, Bytheway JA (2016) Interobserver reliability of the total body score system for quantifying human decomposition. J Forensic Sci 61:445–451. https://doi.org/10.1111/1556-4029.12962
51. Dabbs GR, Bytheway JA, Connor M (2017) Comparing the Scoring of Human decomposition from Digital Images to Scoring using On-site observations. J Forensic Sci 62:1292–1296. https://doi.org/10.1111/1556-4029.13409
52. Forbes MNS, Finaughty DA, Miles KL, Gibbon VE (2019) Inaccuracy of accumulated degree day models for estimating terrestrial post-mortem intervals in Cape Town, South Africa. Forensic Sci Int 296:67–73. https://doi.org/10.1016/j.forsciint.2019.01.008
53. Dawson BM, Wallman JF, Barton PS (2022) How does mass loss compare with total body score when assessing decomposition of human and pig cadavers? Forensic Sci Med Pathol 18:343–351. https://doi.org/10.1007/s12024-022-00481-6
54. Smith DH, Ehrett C, Weisensee K, Tica C Commentary on: Megyesi MS, Nawrocki SP, Haskell NH. Using accumulated degree-days to estimate the postmortem interval from decomposed human remains. J Forensic Sci. 2005;50(3):618–26. doi:, Moffatt C, Simmons T, Lynch-Aird J (2023) An imp. J Forensic Sci 68:355–358. https://doi.org/10.1111/1556-4029.15151
55. Dabbs GR (2010) Caution! All data are not created equal: the hazards of using national weather service data for calculating accumulated degree days. Forensic Sci Int 202:e49–e52. https://doi.org/10.1016/j.forsciint.2010.02.024
56. Reid EK, Tejani AM, Huan LN et al (2015) Managing the incidence of selective reporting bias: a survey of Cochrane review groups. Syst Rev 4:1–8. https://doi.org/10.1186/s13643-015-0070-y
57. Song F, Parekh S, Hooper L et al (2010) Dissemination and publication of research findings: an updated review of related biases. Health Technol Assess (Rockv) 14:1–220. https://doi.org/10.3310/hta14080
58. Dwan K, Altman DG, Arnaiz JA et al (2008) Systematic review of the empirical evidence of study publication bias and outcome reporting bias. PLoS ONE 3. https://doi.org/10.1371/journal.pone.0003081
59. Suckling JK, Spradley MK, Godde K (2016) A longitudinal study on human outdoor decomposition in Central Texas. J Forensic Sci 61:19–25. https://doi.org/10.1111/1556-4029.12892
60. Ceciliason AS, Andersson MG, Lindström A, Sandler H (2018) Quantifying human decomposition in an indoor setting and implications for postmortem interval estimation. Forensic Sci Int 283:180–189. https://doi.org/10.1016/j.forsciint.2017.12.026
61. Marhoff-Beard SJ, Forbes SL, Green H (2018) The validation of 'universal' PMI methods for the estimation of time since death in temperate Australian climates. Forensic Sci Int 291:158–166. https://doi.org/10.1016/j.forsciint.2018.08.022
62. Marhoff SJ, Fahey P, Forbes SL, Green H (2016) Estimating postmortem interval using accumulated degree-days and a degree of decomposition index in Australia: a validation study. Aust J Forensic Sci 48:24–36. https://doi.org/10.1080/00450618.2015.1021378
63. Buekenhout I, Cravo L, Vieira DN et al (2018) Applying standardized decomposition stages when estimating the PMI of buried remains: reality or fiction? Aust J Forensic Sci 50:68–81. https://doi.org/10.1080/00450618.2016.1212268
64. Cameron A, Oxenham M (2020) The postmortem interval and skeletal remains. Estimation of the Time since Death: Current Research and Future trends. Elsevier Inc., pp 141–164
65. Wescott D (2018) Recent advances in forensic anthropology: decomposition research. Forensic Sci Res 3:327–342. https://doi.org/10.1080/20961790.2018.1488571