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ЭКОЛОГИЧЕСКИЕ ОСОБЕННОСТИ ПРОЦЕССА ВЕРМИКОМПОСТИРОВАНИЯ: МЕТААНАЛИЗ

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Для всесторонней оценки качества компоста и закономерностей трансформации тяжелых металлов при вермикомпостировании в различных условиях контроля нами проведен анализ 109 статей. С помощью метаанализа количественно исследовано влияние видов вермикультуры, продолжительности предварительного компостирования, методов вентиляции, начального соотношения C/N, начальной pH и начального содержания влаги на улучшение качества компоста и снижение токсичности тяжелых металлов. Установлено, что все шесть факторов существенно влияют на качество компоста и токсичность тяжелых металлов. После вермикомпостирования достоверно увеличились следующие показатели питательных веществ: NO_3-N – на 116,2 %, общий азот – на 29,1, общий фосфор – на 31,2 и общий калий – на 15,0 %. При этом содержание NH_4^+-N уменьшилось на 14,8 % и соотношение C/N – на 36,3 %. Кроме того, общее количество и биодоступность меди и хрома в конечном компосте также значительно снизились. Учитывая влияние различных факторов группировки на качество компоста и воздействие тяжелых металлов, если основной целью компостирования является содействие разложению и обогащению питательными веществами, то рекомендуется довести начальную влажность компостируемых материалов до 70–80 %, C/N до 30–85 и pH до 6–7, провести предварительное компостирование в течение 315 дней при естественной вентиляции. Если основной целью является снижение опасности тяжелых металлов в материалах, рекомендуется отрегулировать начальное содержание влаги до 50–60 %, соотношение C/N ниже 30, pH до 7–8, пропустить предварительное компостирование, включить регулярное укладывание в штабель и использовать вид *Eudrilus eugeniae* для вермикомпостирования. Эти рекомендации будут способствовать комплексной утилизации куриного помета, дождевых червей и остатков китайских трав, оптимизируя процесс компостирования.

Ключевые слова: компостирование дождевых червей; остатки традиционной китайской медицины; физические и химические свойства.

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ECOLOGICAL FEATURES OF THE VERMICOMPOSTING PROCESS: META-ANALYSIS

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In order to comprehensively assess the compost quality and heavy metal transformation patterns of vermicomposting under various control conditions, we reviewed 109 articles. Through meta-analysis, we quantitatively investigated the effects of vermiculture species, pre-composting duration, ventilation methods, initial C/N ratio, initial pH, and initial moisture content on improving compost quality and reducing heavy metal toxicity. The results indicate that all six grouping factors significantly influence compost quality and heavy metal toxicity. After vermicomposting, the following nutrient indicators significantly increased: NO_3^--N (increased by 116.2 %), total nitrogen (increased by 29.1 %), total phosphorus (increased by 31.2 %), and total potassium (increased by 15.0 %). Meanwhile, NH_4^+-N content (decreased by 14.8 %) and C/N ratio (decreased by 36.3 %) significantly decreased. Additionally, the total amounts and bioavailability of copper and chromium in the final compost also significantly decreased. Considering the significant effects of different grouping factors on compost quality and heavy metal impact, if the primary objective of composting is to promote decomposition and nutrient enrichment, it is recommended to adjust the initial moisture content of composting materials to 70–80 %, C/N ratio to 30–85, and pH to 6–7, and conduct pre-composting for 315 days with natural ventilation. If the main goal is to mitigate heavy metal hazards in the materials, it is advisable to adjust the initial moisture content to 50–60 %, C/N ratio below 30, pH to 7–8, skip pre-composting, turn the pile regularly, and employ the *Eudrilus eugeniae* species for vermicomposting. These recommendations will facilitate the comprehensive utilization of chicken manure, earthworms, and Chinese herbal residue, optimizing the composting process.

Keywords: earthworm composting; traditional Chinese medicine residue; physical and chemical properties.

Introduction

It is estimated that approximately 1.12 billion tons of solid waste are generated globally each year, with about 46 % comprising organic waste, including poultry and livestock manure, sewage sludge, crop residues, kitchen waste, and landscaping debris [1; 2]. These organic wastes contain significant quantities of essential nutrients such as nitrogen, phosphorus, and potassium required for crop growth. However, improper disposal and indiscriminate dumping of these wastes not only result in resource wastage but also contribute to environmental issues, such as air, water, and soil pollution [3]. Aerobic composting has been proven as an effective method for handling organic solid waste and is widely adopted globally [4]. During this process, the transformation of nutrients like nitrogen, phosphorus, and potassium, as well as heavy metals, is a common focus of composting research. The final compost product can serve as organic fertilizer, providing long-term nutrient supply to crops, aligning with modern sustainable agricultural practices. The content of nitrogen, phosphorus, and potassium in compost is crucial in evaluating compost quality [5]. However, global meta-analysis shows that approximately 31.4 % of nitrogen, a key nutrient, is lost during the composting process, with 54.8 % and 4.5 % of the nitrogen loss occurring due to NH_3 and N_2O emissions, respectively [6]. Simultaneously, organic solid waste, such as livestock and poultry manure and sewage sludge, which serve as composting raw materials, often contain elevated levels of heavy metals. After composting, these heavy metal levels may not decrease and could even increase due to concentration effects [7]. Compost products have become a primary source of heavy metals in farmland soil [8]. Although heavy metals can undergo a transformation from available forms to less available forms during composting [9; 10], reducing their toxicity and absorption by crops, the hazard from heavy metals is not entirely eliminated. Therefore, nutrient loss and heavy metal contamination remain pressing issues that need to be addressed in the organic solid waste management process [11; 12]. Vermicomposting is an economically efficient bioprocessing technique that utilizes earthworms and microorganisms to enhance the decomposition and conversion of organic waste into nutrient-rich and stable humus-vermicompost [13]. Compared to traditional composting, vermicomposting offers three prominent advantages. Firstly, earthworms reduce the volume of organic waste by ingesting it and excreting nutrient-rich vermicast, which contains soluble and readily available nutrients such as nitrogen, phosphorus, potassium, and calcium. This is beneficial for microbial growth, ultimately optimizing and accelerating the composting process [2; 14]. Additionally, earthworms can absorb and concentrate heavy metals, effectively reducing their content and altering their forms after ingestion [15]. Secondly, the enzymes secreted in the earthworm's digestive system, such as proteases, esterases, amylases, and cellulases, are essential for the decomposition of organic solid waste, particularly in breaking down cellulose and lignin [16]. Thirdly, earthworm activities and burrowing behavior create a favorable environment with good porosity, aeration, drainage, and a larger surface area, supporting the survival of beneficial microorganisms and enhancing the composting process [13–19]. Mohee, et al. [20] reviewed the comparison of metal contents between organic solid waste composting and vermicomposting and found that the metal dynamics during vermicomposting are complex, yielding varying results in terms of final compost heavy metal content in the literature. Furthermore, the substantial variation could be attributed to factors such as earthworm species, raw materials, amendments, pre-composting time, composting scale, initial parameters, and process control. Considering real-world scenarios, it is impossible to account for all influencing factors and conduct a comprehensive analysis of all indicators in a single study. Thus, it is necessary to provide a comprehensive and quantitative evaluation of the impact of different influencing factors on the transformation of nutrients and heavy metals in vermicomposting. This can effectively guide practical applications. Therefore, in this study, we collected relevant vermicomposting literature and conducted a meta-analysis to quantify the effects of earthworm species, raw material properties (pH, moisture content, and C/N ratio), process control (pre-composting time and ventilation methods) on improving compost quality and reducing heavy metal toxicity. This research aims to provide a theoretical foundation and technical guidance for optimizing vermicomposting technology, which holds significant importance in the resource utilization and environmentally safe management of organic solid waste.

Methodology and data

We conducted a comprehensive literature review using academic databases such as Google Scholar, Elsevier Science Direct, Web of Science, and the Chinese National Knowledge Infrastructure (CNKI). Our search was systematically performed with keywords such as «vermicomposting, heavy metals, bioavailability, nutrient elements, and maturity». The search process is depicted in Figure 1.

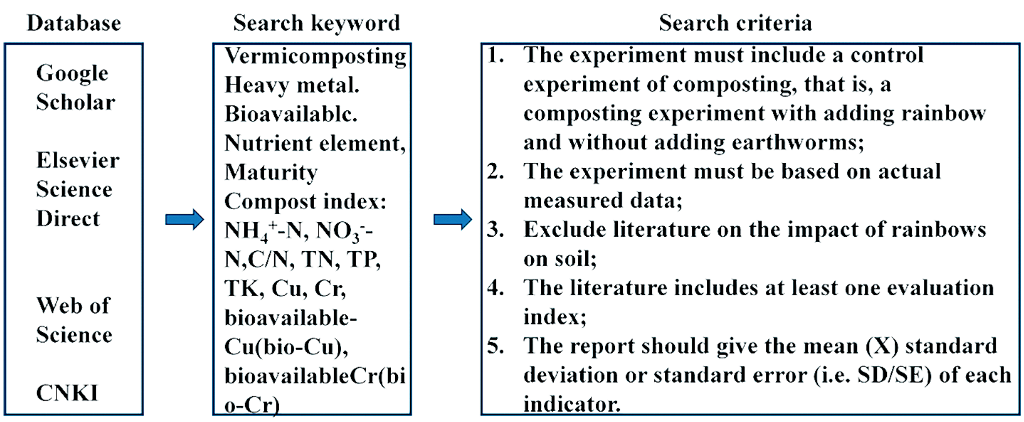

Fig. 1. Literature retrieval process of vermicomposting

When calculating and analyzing using standard deviation (SD), if the literature only provides standard error (SE), you can convert SE to SD using Formula (1):

$$SD = SE * \sqrt{n}. \tag{1}$$

Where *n* represents the number of replicates for each study. In cases where SD or SE is missing in a small number of instances, you can calculate it based on one-tenth of the mean value [21].

Based on the conditions mentioned above, a total of 109 valid articles were obtained.

In this process, we treated various factors as explanatory variables to better understand the changes in the measured indicators. We categorized the data into subgroups based on the objective characteristics of compost (such as initial C/N ratio and initial moisture content), the species of earthworms, and the ventilation methods. When selecting these subgroups, we aimed to ensure that they could collectively explain the variations in all the indicators. We conducted multiple subgroup analyses, such as establishing an initial C/N value of 30 as a boundary, as it provided a relatively better explanatory effect for the indicators.

Ultimately, we determined the following grouping factors and their respective subgroups: earthworm species (including Eisenia fetida, Eudrilus eugeniae, Perionyx excavatus, and mixed species), pre-composting days (no pre-composting, 0–15 days, and 15–65 days), ventilation methods (natural placement, turning piles, and static ventilation), initial C/N (0–30 and 30–85), initial moisture content (50–60 %, 60–70 and 70–80 %), and initial pH (6–7, 7–8, and 8–9).

Additionally, we selected three numerical factors, which played a role similar to grouping factors but were continuous in nature. These numerical factors included initial C/N, initial moisture content, and initial pH. In our study, we extracted data from the selected research, and when data retrieval from figures was required, we used GetData 2.2 software to facilitate this process.

Data selection and pre-processing

The effect size for each study is calculated as the natural logarithm of the relative risk (RR) using Formula (2):

$$lnRR = \ln\left(\frac{XE}{XC}\right). \quad (2)$$

Here, XE represents the data from the experimental group, and XC represents the data from the control group. The heterogeneity of the data is assessed using the results of a heterogeneity test, and a mixed random-effects model is chosen [23] based on 999 data iterations through a bootstrap procedure using MetaWin 2.1 [22]. For each indicator and subgroup, 95 % confidence intervals are generated for the average effect size and bias correction (resulting in equivalent weighted index calculations). For ease of interpretation, the results of lnRR (average effect and confidence intervals) are back-transformed using Formula (3) to display percentage change:

$$\text{Percentage Change} = (\text{RR} - 1) \times 100\,\%. \quad (3)$$

In the results of this study, both positive and negative effect values are used to represent the impact of grouping factors and their subgroups on the quality of vermicompost and heavy metal effects. Positive values indicate a positive effect, such as 25.2 %, which signifies an increase of 25.2 % in a specific indicator (compared to the control group). Negative values represent a negative effect, for example, −32.5 %, which indicates a decrease of 32.5 % in a specific indicator (compared to the control group). If the 95 % confidence interval does not overlap with 0, it is considered to be a significant difference between the experimental group and the control group; otherwise, there is no significant difference. Significant between-group heterogeneity (QB) ($p < 0.05$) indicates a significant difference between certain influencing factors and other factors. However, for subgroups with fewer than 10 samples, the results are considered dubious.

Results and discussion

Assessment of Publication Bias in Vermicomposting Effects on Compost Maturation, Quality, and Heavy Metals. Table 1 presents the results of publication bias assessment for various outcomes. Among these, Kendall's rank correlation coefficients for NH_4^+-N, C/N, NO_3^--N, TN, bioavailable Cu (bio-Cu), Cr, and bioavailable Cr (bio-Cr) exceed 0.05, and their insecurity numbers are greater than 5n+10, indicating that these four indicators are not subject to publication bias. In contrast, Kendall's rank correlation coefficients for TP, TK, and Cu content are less than 0.05, indicating the presence of bias. However, the fact that their insecurity numbers are still greater than 5n+10 suggests that the observed publication bias does not significantly impact the estimation results.

Table 1

Results of publication bias of various indicators

Compost index	Number of studies	Correlation index	Spearman phase Relation number	Fail-safe number	5n+10[1]
NH_4^+-N	56	0.39725	0.39841	5774.1	1030
NO_3^--N	61	0.87052	0.56413	55243.9	12 00
C/N	219	0.05955	0.08216	7732198.1	3260
TN	195	0.25564	0.22291	3264898.8	2870
TP	171	0.04714	0.06031	1113016.8	2160
TK	187	0.00346	0.00639	1503474.2	2850
Cu	195	0.39725	0.06885	345638.2	3045
bio-Cu	82	0.24396	0.33538	34883.0	1145
Cr	59	0.47011	0.55995	6850.8	920
bio-Cr	40	0.47779	0.48284	44581.3	580

Impact of Vermicomposting on Compost Maturation, Compost Quality, and Heavy Metals Cu and Cr: A Meta-Analysis. Our meta-analysis reveals that vermicomposting has a significant optimizing effect on compost quality and reduction of heavy metal hazards. As depicted in Figure 2, following the process of vermicomposting, the content of NO_3^--N, TN, TP, and TK in the final compost increased by 116.2 % (CI: 82.7~155.8 %), 29.1 % (CI: 25.2~33.2 %), 31.2 % (CI: 27.2~35.3 %), and 15.0 % (CI: 8.9~21.6 %), respectively. Meanwhile, the NH_4^+-N content and C/N ratio gradually decreased, resulting in a reduction of 14.8 % (CI: –22.4 ~ –6.3 %) in NH_4^+-N content and 36.3 % (CI: –40.0 ~ –32.5 %) in the C/N ratio in the final compost.

Furthermore, vermicomposting significantly reduced the total Cu content by 10.2 % (CI: –12.9 ~ –7.4 %) and the total Cr content by 15.5 % (CI: –23.7 ~ –6.4 %) in the compost. It also decreased the bioavailability of Cu and Cr by 20.7 % (CI: –24.0 ~ –17.3 %) and 41.1% (CI: –46.9 ~ –34.6 %), respectively. This comprehensive analysis highlights the beneficial effects of vermicomposting on compost quality and its ability to mitigate the presence of heavy metals Cu and Cr.

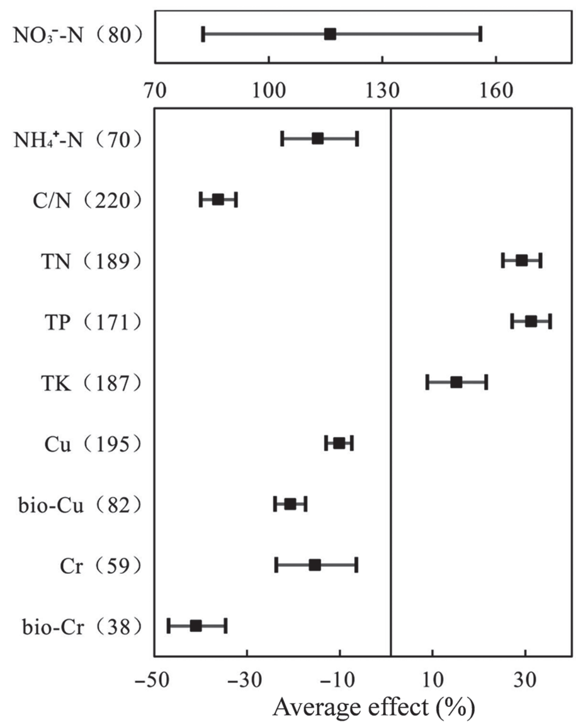

Fig. 2 Total effects of vermicomposting on maturity, nutrient elements, and heavy metals

Impact of Grouping and Numerical Factors on Compost Maturation and Compost Quality. In order to optimize the composting process and promote microbial degradation, vermicomposting imposes strict limits on initial parameters such as moisture content, C/N ratio, and pH. The results of the meta-analysis reveal that the recommended ranges for initial moisture content, C/N ratio, and pH are generally within 50 to 80 %, 5 to 85, and 6 to 9, respectively. Although the C/N ratio has a relatively broad range, other parameters align closely with the recommended guidelines of Bernal, et al. [25]. The average values for initial moisture content, C/N ratio, and pH are 65.4 %, 28.4, and 7.5, respectively.

Regarding the initial C/N ratio, there are 133 observations within the range of 5 to 30, which is significantly higher than the 70 observations within the range of 30 to 85. A low C/N ratio might lead to increased losses of TN and NH_3, while a high C/N ratio may slow down the composting process. Therefore, it is advisable to regulate the initial C/N ratio to be around 28. Gao, et al. [26] also found that an initial C/N ratio of 28 was effective in improving the stability and maturation of compost in forced aeration composting experiments involving a mixture of chicken manure and sawdust.

In terms of moisture content, the range of 60 to 70 % is more prevalent, with an average value of 65 %. This moisture range is considered most suitable for microbial activity and promotes an optimal microbial environment.

Regarding the species of earthworms, *Eisenia fetida* is a readily available species and has been widely employed by researchers. In industrial-scale production, many operations skip the pre-composting step to expedite composting times (with 99 studies not utilizing pre-composting). However, pre-composting of solid waste plays a crucial role in subsequent vermicomposting processes [27; 28]. On one hand, high-temperature pre-composting effectively eliminates pathogens and harmful bacteria from the waste material [29]. Additionally, it allows earthworms to thrive without being affected by elevated temperatures [30]. On the other hand, harmful gases like NH3 can be released during the pre-composting phase to reduce potential harm to earthworms [31]. A significant portion of the studies (85 in total) conducted pre-composting experiments lasting from 3 to 15 days to create an environment more favorable for earthworm survival.

In terms of ventilation methods, vermicomposting differs from traditional composting. Earthworm activities, including feeding, movement, and burrowing, naturally increase the porosity of the composting material [32]. As a result, adequate oxygenation for microorganisms can be achieved without the need for static ventilation or turning piles. Hence, natural placement studies are the most prevalent (with 185 studies) in the context of vermicomposting research.

Impact of Grouping Factors on Vermicomposting Maturation. As illustrated in Figure 3*a*, when considering earthworm species, the addition of Eisenia fetida (–17.1 %) and a mixture of various earthworm species (–18.8 %) proved effective in reducing NH_4^+-N content. In the case of pre-composting days, pre-composting for 0–15 days (–23.5 %) significantly reduced NH_4^+-N content in the compost. Furthermore, when it comes to ventilation methods, natural placement (–13.4 %) was notably effective in reducing NH_4^+-N content in the compost. In terms of initial material properties, the initial moisture content in the range of 70 to 80 % (–29.9 %), C/N ratios in the range of 0–30 (–16.8 %), and initial pH values in the range of 6–7 (–38.6 %) all led to significant reductions in NH_4^+-N content.

Similar to regular composting, vermicomposting is a process that gradually converts NH_4^+-N into NO_3^--N, signifying the maturation of compost [33]. As shown in Figure 3*b*, after vermicomposting, the NO_3^--N content significantly increased, potentially due to alterations in bacterial community diversity and structure within the earthworm gut. These changes could promote organic matter degradation, nitrogen mineralization, and NH_4^+-N nitrification [34]. Among earthworm species, vermicomposting with a mixture of various earthworm species resulted in the highest NO_3^--N increase (156.7 %), surpassing the effects of using *Eisenia fetida* (61.3%) and *Eudrilus eugeniae* earthworms (121.9 %). In terms of pre-composting days, no pre-composting significantly increased NO_3^--N content (143.2 %), followed by 0–15 days (110.5 %) and 15–65 days (78.0 %). An initial moisture content of 70 to 80 % effectively increased NO_3^--N content (147.1 %), followed by 60 to 70 % (116.3 %) and 50 to 60 % (104.4%). While ventilation methods and initial pH grouping had no significant impact on NO_3^--N in vermicomposting, natural placement and an initial pH range of 6–7 significantly increased NO_3^--N content by 120.6 and 134.0 %, respectively.

The ratio of NH_4^+-N to NO_3^--N content can be used to assess compost maturation. Statistical analysis reveals that the final compost's NH_4^+-N content ranged from 0.004 to 4.7 $g \cdot kg^{-1}$, with an average of 1.0 $g \cdot kg^{-1}$. The NO_3^--N content in the final compost ranged from 0.01 to 30.5 $g \cdot kg^{-1}$, with an average content of 2.7 $g \cdot kg^{-1}$. The ratio of NH_4^+-N to NO_3^--N content averaged 0.37, which is below 1, meeting the requirements for compost maturation [35].

Additionally, the C/N ratio is an important indicator for evaluating compost maturation and stability [36]. As shown in Figure 3*c*, the use of a mixed earthworm species significantly reduced the C/N ratio (–54.6 %). This was followed by Perionyx excavatus (–46.0 %), Eisenia fetida (–36.2 %), and Eudrilus eugeniae (–23.9 %). The highest reduction in C/N occurred with pre-composting for 0–15 days (–43.4 %), followed by no pre-composting (–34.2 %) and 15–65 days (–25.7 %). Proper pre-composting treatment can facilitate the breakdown of some refractory organic matter to a level acceptable to earthworms, enhancing the efficiency of organic matter decomposition [37]. Under natural placement and turning pile ventilation conditions, vermicomposting significantly reduced the C/N ratio by 38.7 and 22.3 %, respectively. In the case of natural placement, earthworm activities led to the breakdown of compost substrate from larger particles to uniform smaller ones, improving aeration and oxygen levels, increasing the effective microbial surface area, and accelerating organic matter decomposition [38]. The greatest reduction in the C/N ratio occurred when the initial moisture content was 70 to 80 % (–45.6 %), followed by 60 to 70 % (–30.1 %) and 50 to 60 % (–29.8 %). This phenomenon may be due to the higher moisture content promoting the emission of methane gas from methane-producing bacteria in the compost matrix. When the initial C/N ratio of the compost was in the range of 30–85 (–45.3 %), the C/N ratio significantly decreased. This was followed by the range of 0–30 (–27.2 %). Research by Aira et al. suggested that when the initial C/N ratio is high, earthworms prioritize reproduction over growth, resulting in a higher population of earthworms that consume more organic carbon. As a result, the final compost C/N ratio decreases more significantly. When the initial pH was between 6–8, earthworm activities and microbial activity were higher, accelerating the breakdown of organic nitrogen and causing nitrogen loss. The statistical analysis of all observations showed that the final compost's C/N ratio ranged from 1.1 to 52.7, with an average of 13.8, which is less than 15, meeting the requirements for compost maturation.

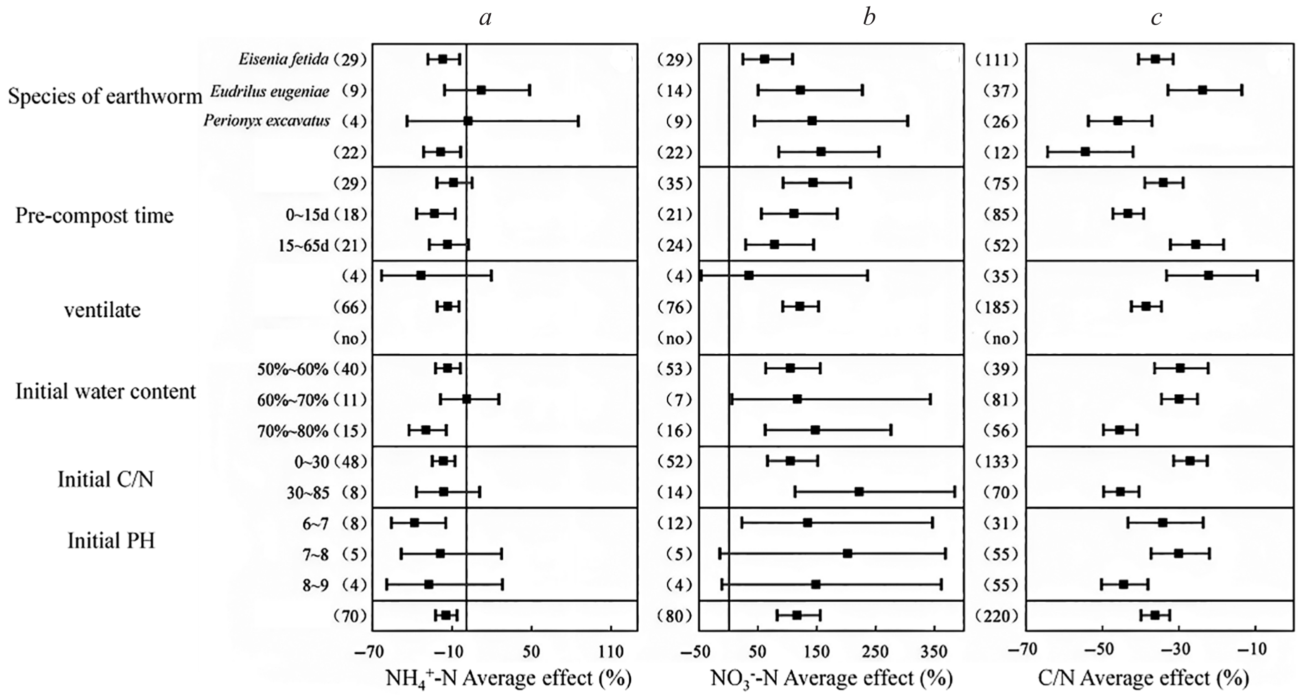

Fig. 3. Effects of different grouping factors on the change efficiency of NH_4^+-N, NO_3^--N, and C/N

Impact of Grouping Factors on Vermicomposting Quality. After earthworms decompose organic matter, the mineralization of substances rich in nitrogen, such as their nitrogen-rich excreta containing microorganisms, secreted polysaccharides, hormones, and enzymes, contributes to the increased nitrogen content in the compost. Additionally, during the mineralization process, the evaporation of moisture generated by the decomposition of organic nitrogen compounds can potentially lead to a relative increase in nitrogen content. As depicted in Figure 4*a*, the combined use of various earthworm species (69.5 %) exhibited a higher increase in TN, surpassing the effects of individual earthworm species. Regarding pre-composting days, the effects of 0–15 days (25.1 %) and 15–65 days (25.2 %) were slightly lower than that of no pre-composting (31.7 %). Among ventilation methods, natural placement proved to be the most effective (38.4 %), while static ventilation methods led to a reduction in TN content in vermicompost, with no significant effect (–7.3 %). This phenomenon may be attributed to the earthworms' burrowing behavior, which promotes compost aeration conditions, optimizes microbial community structure, and enhances the efficiency of vermicomposting, thereby facilitating the accumulation of nutrients. When the initial C/N of the vermicompost was in the range of 30–85, the TN content in the vermicompost increased the most (55.6 %), while the smallest increase occurred in the range of 0–30 (19.2 %). Liu et al. demonstrated through meta-analysis that nitrogen loss in compost decreases with an increase in the initial C/N ratio. This could be due to the fact that if the initial C/N is too low, there is an excessive supply of nitrogen, which can easily lead to nitrogen loss. Jiang et al. found that in pig manure composting, a lower initial C/N ratio (15) results in higher NH_3 and N_2O emissions than when the initial C/N is 30. Additionally, Wong, et al. discovered in experiments involving composting animal remains from slaughterhouses that a lower initial C/N ratio (16) leads to an 84 % initial loss of NH_4^+-N. This may be because excessively low C/N ratios can lead to an accumulation of excess nitrogen, which can stimulate NH_3 emissions. When the initial pH was in the range of 8–9, the TN content in vermicompost increased the most (48.2 %), followed by a pH range of 6–7 (27.7 %) and 7–8 (15.0 %). This may be because earthworms and the microorganisms in the compost are more active in a neutral pH environment. The vigorous biological activity promotes the decomposition of organic nitrogen in the compost, making nitrogen loss more likely.

As vermicomposting progresses, the rapid decomposition of organic matter leads to an enrichment effect, resulting in an increase in TP and TK in vermicompost. Additionally, earthworm gut phosphatases and phosphorus-dissolving microorganisms release the bioavailable components of phosphorus from organic matter. As shown in Figure 4*b*, apart from the ventilation method, all other five grouping factors significantly influence the TP content in vermicompost.

Concerning earthworm species, adding a mixture of earthworms has the greatest effect on increasing TP content (102.1 %). No pre-composting, 0–15 days, and 15–65 days of pre-composting all significantly increase TP content (33.3%, 33.0, and 28.4 %, respectively), with little difference between them. Under natural placement conditions, vermicompost exhibits the greatest increase in TP content (39.8 %). When the moisture content of compost is in the range of 50–60 %, TP content in vermicompost increases the most (69.9 %), while it is the least in the range of 60–70 % (12.7 %). When the initial C/N of the compost is in the range of 30–85, TP content increases the most (45.6 %), with the smallest increase observed in the range of 0–30 (25.9 %). Vermicompost exhibits the greatest increase in TP content when the initial pH is in the range of 8–9 (52.5 %), followed by a pH range of 7–8 (28.2 %) and 6–7 (24.4 %).

As shown in Figure 4*c*, the earthworm Perionyx Excavatus has the greatest effect on increasing TK content (37.2 %), while the effect of the *Eisenia Fetida* earthworm is minimal and not significant (3.6 %). The pre-composting duration significantly affects the TK content of vermicompost only when pre-composting is done for 0–15 days, resulting in a 28.0 % increase. Adequate pre-decomposition of compost materials aids in the digestion and absorption by earthworms, eventually increasing the nutrient content. Among ventilation methods, only natural placement significantly increases TK content by 18.5 %. When the compost moisture content is in the range of 70–80 %, TK content increases by 35.8 %, followed by the range of 60–70 % (11.2 %). In the grouping based on the initial pH, only a pH range of 6–7 significantly increases TK content by 19.9 %.

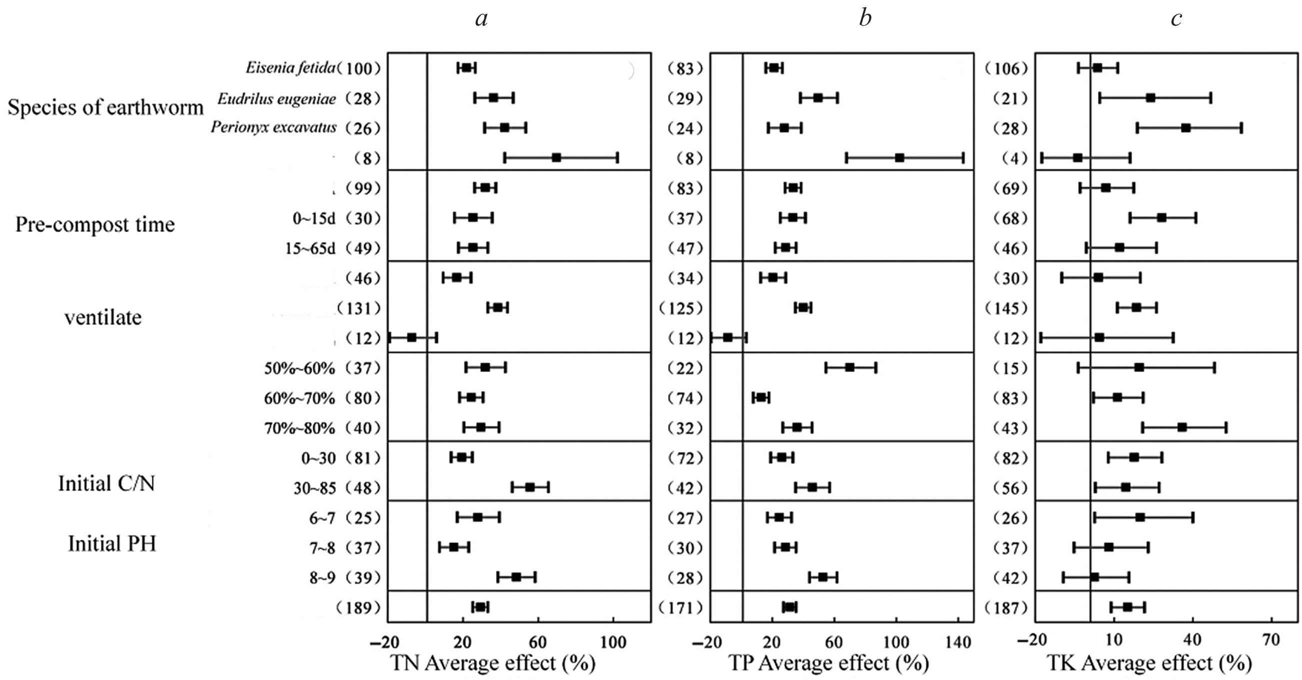

Fig. 4. Effects of different grouping factors on the change efficiency of TN, TP, and TK

Figures 5–7 clearly demonstrate that the initial C/N, pH, and moisture content significantly influence the final C/N, TN, TK, and TP content in vermicompost. Figures 5*c* and 5*f* reveal a significant negative correlation between the initial C/N and the final C/N and TK content of vermicompost. Conversely, there is a significant positive correlation between the initial C/N and TN content, indicating that the TN content in vermicompost increases with an increase in the initial C/N. Figure 5*d* shows that studies with an initial C/N of less than 20 account for 38.3 % of the total, resulting in a relatively lower effect value for TN increase in vermicompost. Furthermore, there is a significant quadratic relationship between the initial C/N and the final TP content in vermicompost, as shown in Figure 5*e*. When the initial C/N is 49.3, vermicompost exhibits the maximum effect value for TP increase at 65.3 %.

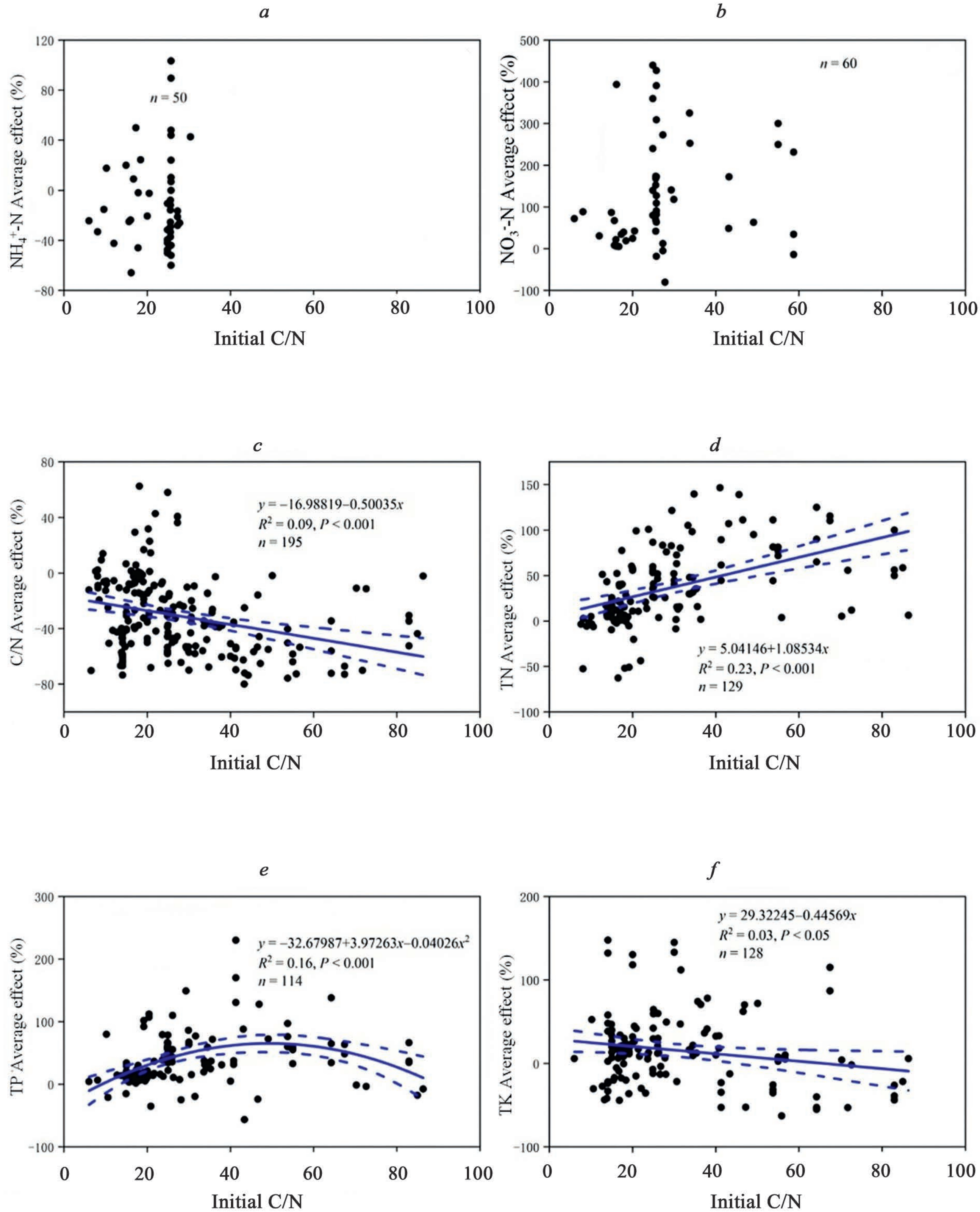

Fig. 5. Relationship between the initial C/N of compost and the change efficiency of NH_4^+-N, NO_3^--N, C/N, TN, TP, and TK

Figures 6*c* and 6*e* reveal a significant negative correlation between the initial pH and the final C/N in vermicompost, while a significant positive correlation is observed with the TP content. Moreover, there is a significant quadratic relationship between the initial pH and the final TN content in vermicompost, as depicted in Figure 6*d*. When the initial pH is 7.08, vermicompost exhibits the minimum effect value for TN increase at 24.5 %.

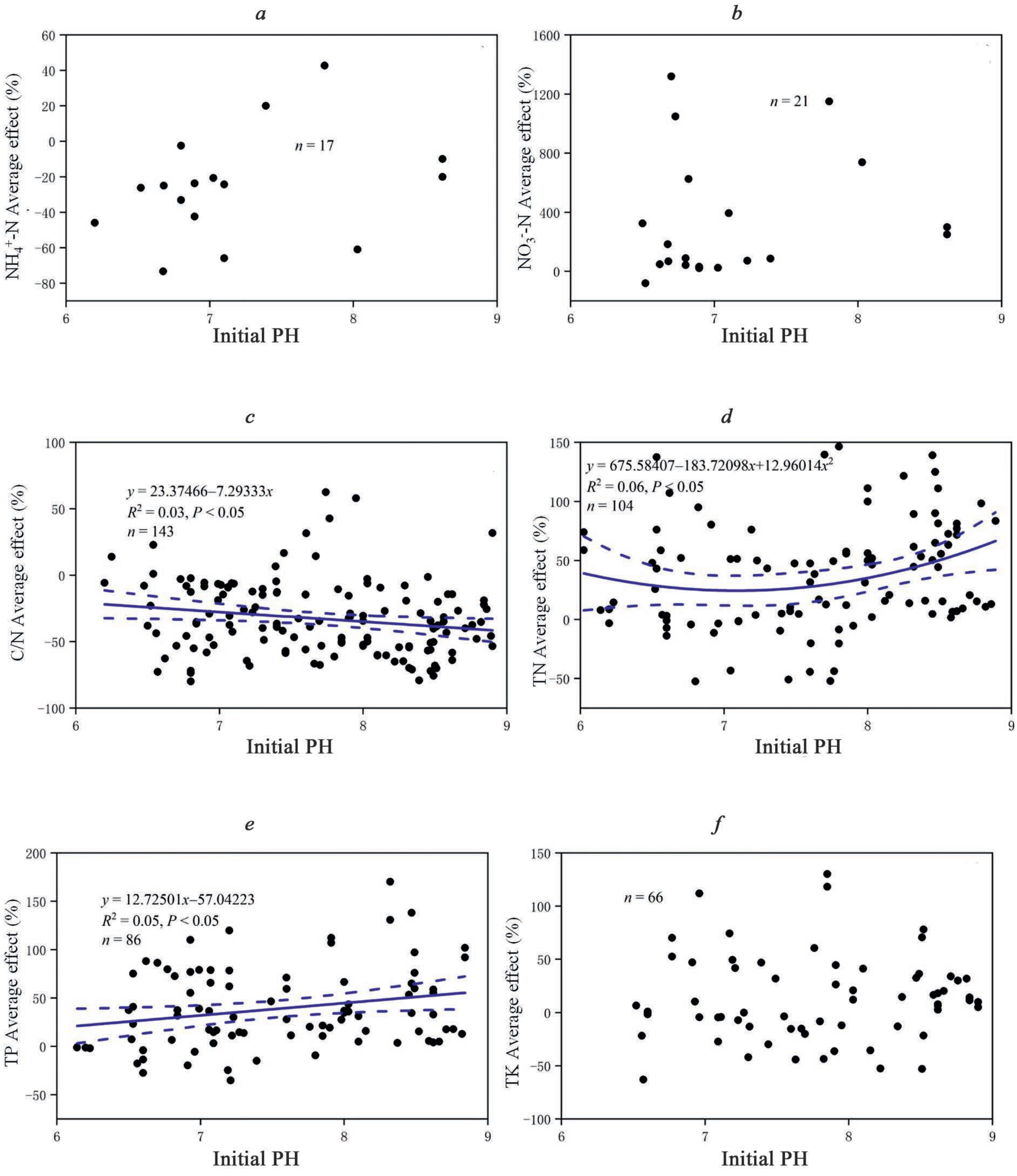

Fig. 6. Relationship between initial pH of compost and changing effect of NH_4^+-N, NO_3^--N, C/N, TN, TP, and TK

As shown in Figure 7*a*, the initial moisture content demonstrates a significant negative correlation with the final NH_4^+-N content in vermicompost. The relationship between the initial moisture content and the final TP content is captured by a significant quadratic equation, as seen in Figure 7*e*. By calculation, it is determined that when the initial moisture content is at 69.5 %, vermicompost exhibits the least increase in TP content, with an increment of 16.1 %.

The initial moisture content and its relationship with the final C/N content is represented by a significant cubic equation, as shown in Figure 7*c*. The calculations indicate that when the initial moisture content is at 70.4 %, vermicompost shows the most substantial decrease in C/N content, with a reduction of 41.6 %.

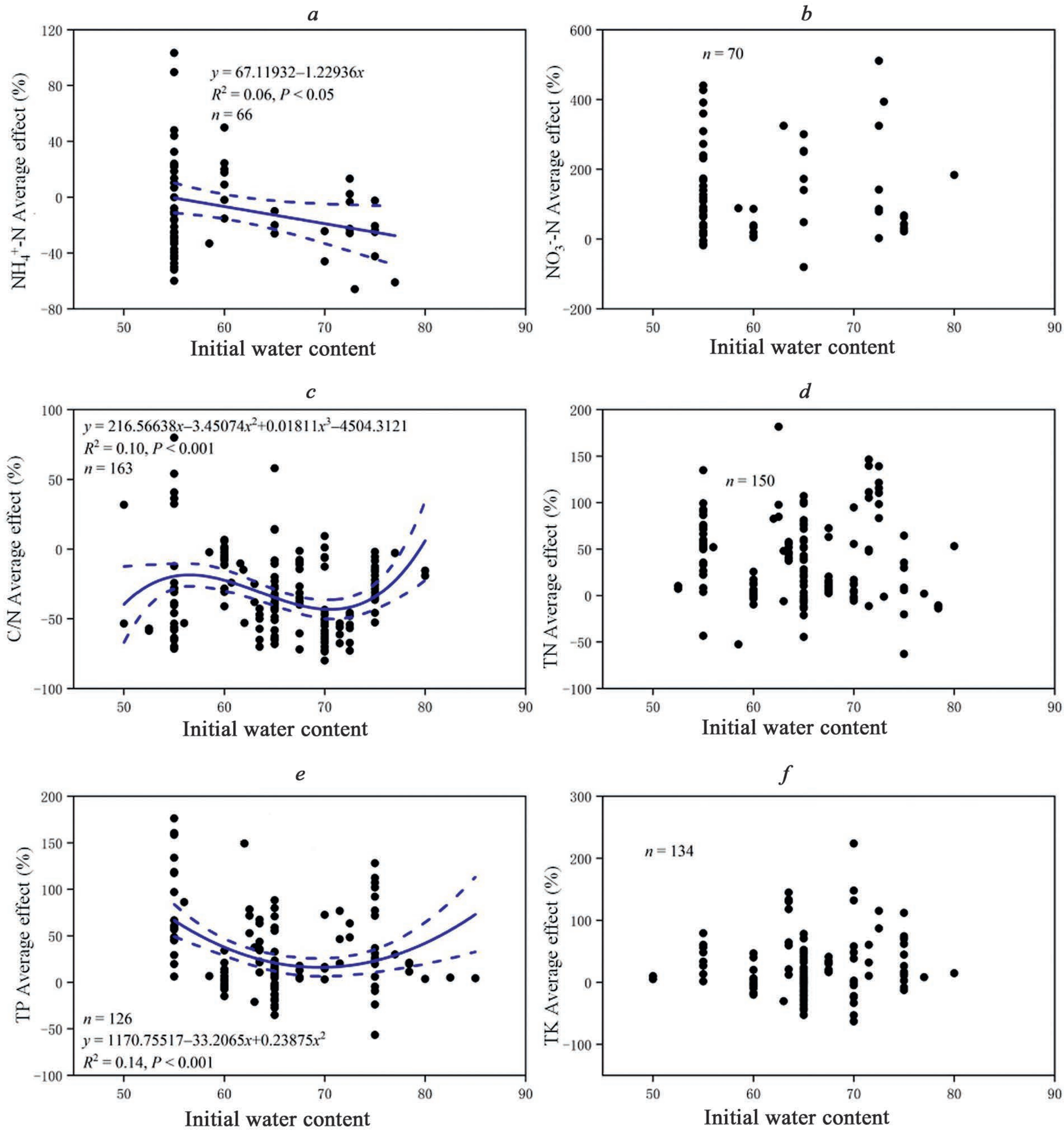

Fig. 7. Relationship between initial moisture content of compost and change effect of NH_4^+-N, NO_3^--N, C/N, TN, TP, and TK

Conclusion

This study conducted a meta-analysis to integrate all available literature data related to vermicomposting, which includes chicken manure and Chinese herbal residue, and its association with nutrient elements and heavy metals. The findings revealed that vermicomposting significantly enhances compost quality while reducing the harmful effects of heavy metals.

Following vermicomposting, the compost saw a notable increase in NO_3^--N, TN, TP, and TK content by 116.2 %, 29.1, 31.2, and 15.0 %, respectively. Simultaneously, NH_4^+-N content and C/N ratio decreased by 14.8 and 36.3 %, respectively. The total amounts of Cu and Cr in the compost were significantly reduced by 10.2 and 15.5 %, and the bioavailability of Cu and Cr decreased by 20.7 and 41.1 %, respectively.

The study also conducted a comparative analysis of the effects of different types of earthworms, pre-composting duration, ventilation methods, initial moisture content, initial pH, and initial C/N on various vermicomposting indicators. The results suggest that to promote compost maturation and nutrient enrichment, it is advisable to adjust the initial moisture content of the materials to the range of 70 to 80 %, maintain a C/N ratio between 30 and 85, keep the pH in the range of 6 to 7, and conduct a pre-composting phase lasting 3 to 15 days. The natural placement of vermicomposting works best under these conditions.

On the other hand, if the goal is to reduce the total amount of heavy metals in the compost and mitigate their harmful effects, it is recommended to adjust the initial moisture content of the materials to the range of 50 to 60 %, maintain a C/N ratio below 30, keep the pH between 7 and 8, refrain from pre-composting, and utilize the *Eudrilus eugeniae* species of earthworms for vermicomposting.

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