Impact of NPK, Plant Residue, Soil Type, and Temperature on the Half-Life of Atrazine Herbicide

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Article

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Abstract

Laboratory experiments were conducted to investigate the effects of NPK fertilization, soil type (silty clay and sandy loam) with no history of pesticides application, temperature (28 and 40C°) and maize residue on half-life reduction of atrazine herbicide. The NPK fertilizer was applied at 375 mg N, 187.5 mg P and 187.5 mg K per 600 g soil, while Maize straw was added at rates 12 g/ 600g soil. Atrazine was applied in four concentrations; 0.0678, 1.69, 3.39 or 5.08 mg g^{-1} soil. The residual atrazine concentration was measured using gas chromatography over a 150-day period. The results showed that degradation of atrazine was highest in Algeraif soil incubated at 40°C (87%), followed by Algeraif soil incubated at 28°C (68%), and Gerif soil at 28°C (54.2%).". Addition of NPK and maize straw significantly enhanced atrazine degradation, with degradation reaching 97% at an at atrazine concentration of 0.0678 mg g^{-1} soil after 150 days. The lowest half-lives compared to control were 125, 39, 25,19 and 14 days with the application of Gerif soil (28 C°), Algeraif soil (28 C°), Algeraif soil (40 C°), NPK and maize straw respectively at atrazine concentration of 5.08 mg g^{-1} soil. In conclusion, the addition of NPK fertilizer and maize straw significantly improved the degradation of atrazine, reducing both its concentration and half-life in soil.

Keywords: atrazine; NPK; plant residue; degradation; persistence

1. Introduction

Pesticides play a vital role in enhancing agricultural productivity to meet the food demands of a growing global population by protecting crops from pests, weeds, and diseases, they contribute significantly to the sustainability of food supply systems for both humans and animals. However, the

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intensive and often indiscriminate application of pesticides in modern agriculture has raised serious concerns regarding their environmental and human health impacts [1,2]. Among these concerns, soil contamination stands out as a critical issue, given that soil serves as the primary sink of pesticide residues following agricultural application.

Persistent pesticide residues in soil can negatively affect the native microbial communities, which are fundamental to nutrient cycling, organic matter decomposition, and maintaining soil health. Disruption of these microbial communities may interfere with elemental cycles such as nitrogen, phosphorus, and carbon and the bioaccumulation of toxic substances in food chains. Moreover, the horizontal and vertical mobility of certain pesticide compounds in soil profiles, increasing the risk of surface and groundwater contamination [3–6].

Given the environmental and health risks associated with the accumulation of pesticide residues in soil, food, and water systems, there is an urgent need to develop effective, safe, and economically viable methods for pesticide remediation. Among these, biodegradation, using soil microorganisms to break down and detoxify organic pollutants, has emerged as one of the most promising strategies [7,8]. Microbial degradation is a natural, cost-effective, and environmentally friendly approach that leverages the metabolic capabilities of native or introduced microbes to transform hazardous pesticide residues into non-toxic compounds.

The efficiency of pesticide biodegradation in soil is influenced by a range of factors, including the physicochemical properties of the pesticide (e.g., solubility, concentration, chemical structure), soil characteristics (e.g., texture, pH, temperature, moisture, organic matter content, salinity), and the presence and activity of microbial populations capable of degrading the compounds [9–14]. Additionally, soil amendments such as organic (e.g., crop residues) and inorganic (e.g., NPK) fertilizers can significantly enhance microbial activity by providing essential nutrients, thereby stimulating the production of enzymes involved in herbicide degradation [15–18].

Understanding the effect of these abiotic factors is essential for developing effective soil management practices and aimed at minimizing the environmental footprint of agrochemical. Therefore, the objective of this study was to investigate the role of soil microorganisms in reducing the half-life of the herbicide atrazine under varying conditions, including the application of organic and inorganic fertilizers, across different soil types and temperature regimes.

2. Materials and Methods

2.1. Data Collection

Soil samples were collected from Al Geraif (Blue Nile bank) area East Khartoum, Sudan where there is no history of pesticide application. Samples were randomly taken with an auger from the top 15cm from different parts in the selected site. Large clods were crushed to a uniform size, mixed thoroughly to make a composite sample and air dried at room temperature. The chemical and physical characteristics of the Al Geraif soil were as follows: pH = 7.8; ECe = 0.69; N = 0.18%; P as P_2O_5= 0.0034%; K as K_2O = 0.03%; Clay = 52.0%; Silt =47.3%; Sand % =0.7%; organic matter = 0.62%. Soils were then divided into five 600g lots and transferred into 1000 ml beaker. Five sets of atrazine concentrations of 0.0, 0.0678, 1.69, 3.39 or 5.08 (mg g^{-1} soil), each for two fertilizers additives and control set were prepared and mixed thoroughly.

The inorganic NPK were added in the urea, P_2O_5, and KCL at rate 375, 187.5 and 187.5 mg per 600g of atrazine-amended soils respectively. Maize straw was added at a rate of 12 g / 600g of atrazine-amended soils. Soils were then wetted with water to 60 % of field capacity mixed thoroughly and incubated in the dark (at 28^0C) for 150 days. At zero time and then after 15, 30, 60, 90, 120 and 150 days, soil samples were taken for determination of atrazine residue. Atrazine residues was determined according to the method described in [19].

To study the effect of soil type on the half-life of Herbicide atrazine similar experiment (Control without addition fertilizers) was repeated using Shambat Gerif (River Nile Bank), north of Khartoum, Sudan. The chemical and physical characteristics of the Gerif soil were as follows: pH = 7.3; ECe =

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0.58; N = 0.11%; P as P_2O_5= 0.43%; K as K_2O = 0.13%; Clay = 31.7%; Silt =53.6%; Sand % =14.7%; total organic carbon = 0.36%; organic matter = 0.31(%).

Determination of atrazine half –life in soil

Residues of atrazine in soil after 150 days incubation were used to calculate the half-life of the herbicides using the following equation suggested by Mulier *et al*., (2006):

$$T½ = \frac{0.693}{K} \quad \text{..... (1)}$$

Where:

T½ = the half - life.

K= the degradation rate constant.

The degradation rate constant can be calculated with the following equation:

$$k = \frac{2.303}{t} \log (c_0/c_t) \quad \text{.....(2)}$$

Where:

C_0 =the initial concentration (ppm)

C_t = concentration at time t (ppm).

2.2. Statistical Analysis

Data were analyzed using Statistica software. A one-way ANOVA was performed separately for each soil treatment to evaluate the effect of atrazine concentrations (0.678–5.80 mg g^{-1} soil). When significant differences were found ($p < 0.05$), Tukey's HSD test was applied, and means were labeled with different letters to indicate statistically significant differences between concentration levels.

3. Results

3.1. Factors Affecting Atrazine Persistence in Soil: Influence of Temperature, Fertilization, and Soil Type

Atrazine degradation in soil was affected by temperature, fertilization, and soil type. The half-life of atrazine was higher at lower temperatures compared to higher temperatures. For instance, in non-fertilized Algeraif soils incubated at 28 ºC, the half-life ranged from 90 to 39 days, whereas at 40 ºC it decreased significantly, ranging between 36 and 25 days. Fertilization also had a strong influence on atrazine persistence. In Algeraif soils incubated at 28 ºC, the half-life ranged from 90 to 39 days in non-fertilized soils, but it decreased to 19–25 days in soils amended with NPK and to 14–22 days in soils amended with plant residue. Moreover, soil type played a significant role in the persistence of atrazine. The half-life in Algeraif soil ranged from 39 to 90 days, while in Gerif soil it was longer, ranging between 70 and 125 days. These results indicate that higher temperatures, fertilization, and soil characteristics significantly accelerate the degradation of atrazine in soil (Table 1).

Table 1. Half –life (days) of various concentrations of atrazine in soils after 150 days of incubation.

Atrazine concentration mg g-1 soil	Gerif soil incubated at 28ºC	Algeraif soil incubated at 28ºC	Algeraif soil incubated at 40ºC	Algeraif soil incubated at 28ºC and fertilized with NPK	Algeraif soil incubated at 28ºC with plant residues
0.678	70^{b}	90^{a}	36^{a}	25^{a}	22^{a}
1.69	84^{b}	60^{b}	30^{b}	21^{b}	20^{b}
3.39	69^{b}	45^{c}	28^{b}	20^{b}	15^{c}
5.80	12^{5a}	39^{c}	25^{b}	19^{b}	14^{c}
P-value	0.004	> 0.001	0.018	0.023	0.009

Different letters within each column indicate significant differences at $p < 0.05$.

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3.2. Effect of Initial Atrazine Concentration on Degradation Rate

The study revealed that the degradation rates of atrazine were inversely proportional to its initial concentrations. In Gerif soil, degradation of all atrazine concentrations started early during the incubation period. However, only 5% degradation was recorded for the maximum concentration after 15 days, increasing to 54.2% after 150 days. At the same time intervals, degradation for the minimum concentration was 12.2% and 7%, respectively (***Figure 1***).

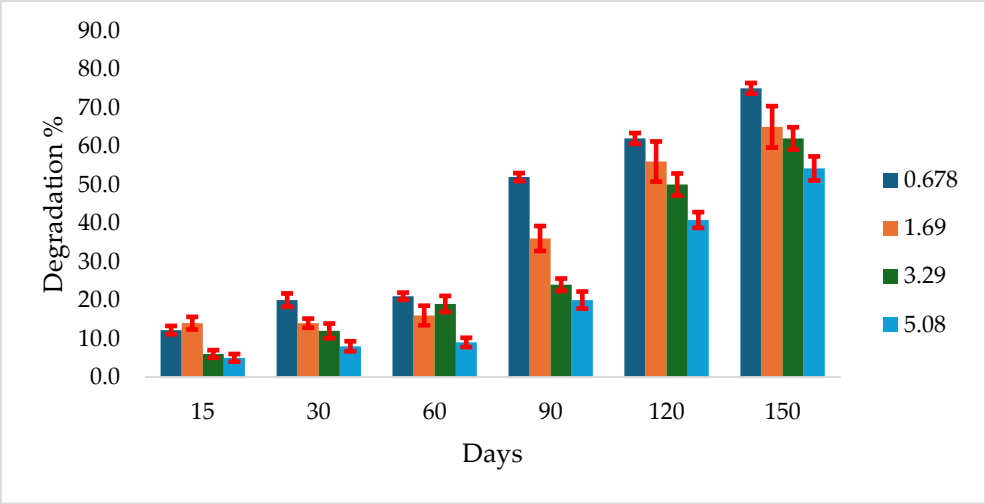

Figure 1. Atrazine degradation rates in Greif soil incubated at 28ºC.

3.3. Atrazine Degradation in Algeraif Soil at 28 ºC

In Algeraif soil incubated at 28 ºC, atrazine degradation was generally low at all tested concentrations. After 15 days of incubation, the degradation percentages were 8%, 9.4%, 10.4%, and 14% for concentrations of 5.08, 3.39, 1.69, and 0.0678 mg g^{-1} soil, respectively. By 150 days, the degradation had increased to 72.0%, 70.0%, 69.3%, and 68% for the same respective concentrations (***Figure 2***).

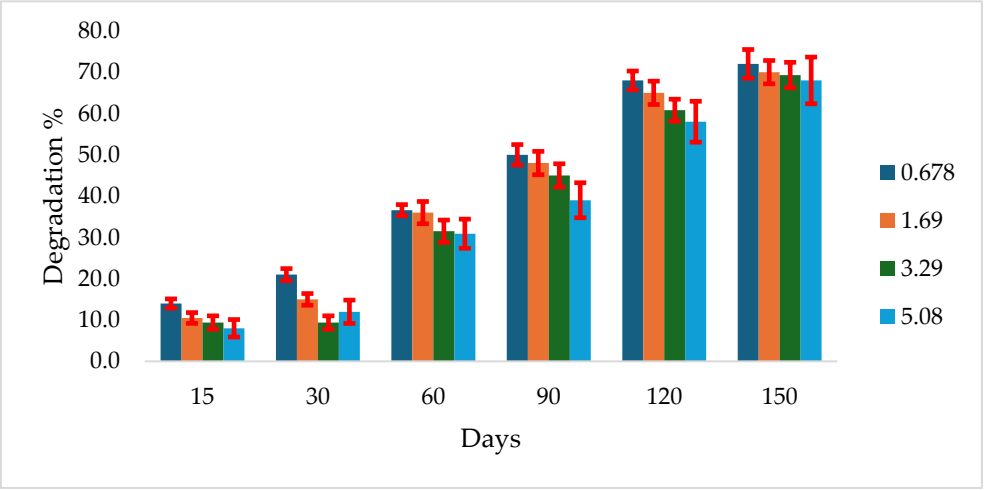

Figure 2. Atrazine degradation rates in Algeraif soil incubated at 28ºC.

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3.4. Atrazine Degradation in Algeraif Soil at 40 ºC

In Algeraif soil incubated at 40 ºC, degradation started earlier for the lower concentrations. After 15 days, 62.5% degradation was recorded at 1.69 mg g^{-1} soil, while 28% and 42% were degraded at 0.0678 and 3.39 mg g^{-1} soil, respectively. After 150 days, a degradation range of 55.2% to 87.0% was observed across all concentrations (***Figure 3***).

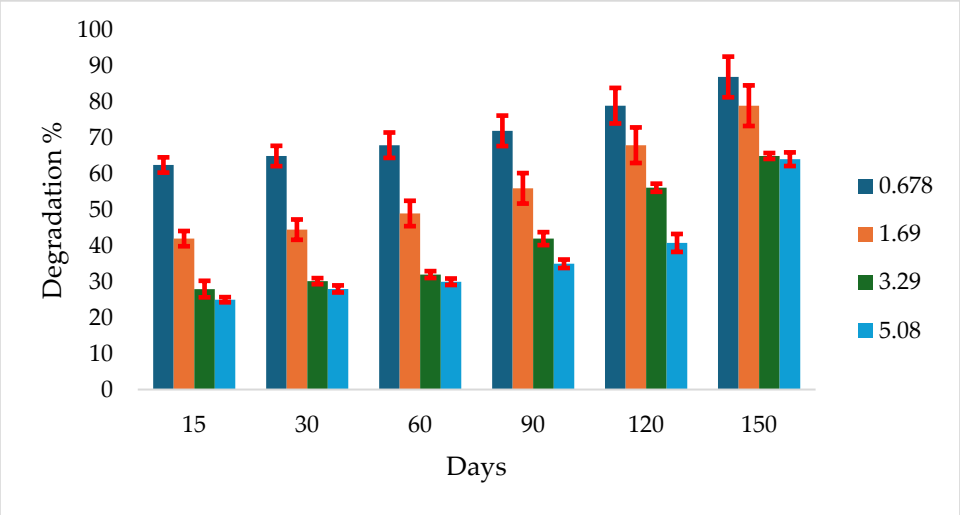

Figure 3. Atrazine degradation rates in Algeraif soil incubated at 40ºC.

3.5. Effect of NPK and Plant Residue on Atrazine Degradation

Soil amendments with NPK and plant residue significantly enhanced atrazine degradation compared to the control. At a concentration of 0.0678 mg g^{-1} soil, 79% degradation was recorded at 120 days with NPK addition, while 91% degradation occurred earlier in plant residue–amended soils. At 1.69 mg g^{-1} soil, NPK induced 82% degradation at 150 days, while plant residue led to faster degradation. At 3.39 mg g^{-1} soil, NPK resulted in 60% degradation at 120 days, again occurring earlier with plant residue. At the highest concentration (5.08 mg g^{-1}), both NPK and plant residue fertilizers promoted intensive degradation as early as 30 days. The maximum degradation recorded was 97% at 150 days for both NPK and plant residue amendments (***Figure 4 A and B***).

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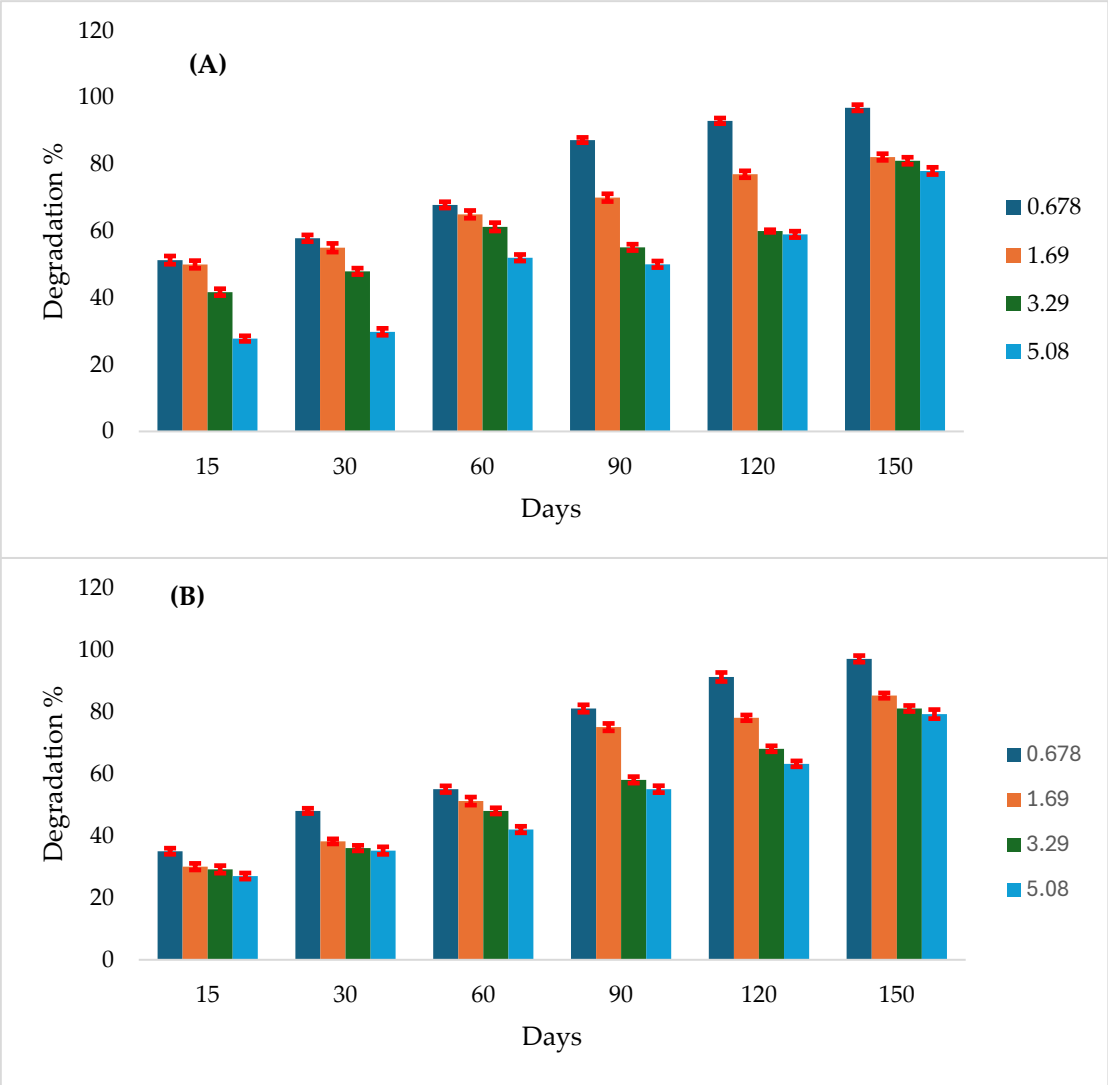

Figure 4. Atrazine degradation rates in Algeraif: **A**: Soil amended with NPK, incubated at 28ºC, and **B**: Soil amended with plant residue, incubated at 28ºC.

4. Discussion

The present study demonstrates that the half - life of atrazine was longer at low temperature compared to higher temperature. Temperature is a key climatic factor, and the increased temperature significantly increased both the biological metabolic processes and the rate of chemical reactions. In this context, [20,21] stated that a rise of 10°C in temperature decreased apparent half-life of pesticides by a factor of 2-3 times. Elevated temperatures not only accelerate the microbial growth but also enhance both biological and chemical processes involved in pesticide dissipation [22–25]. Rapid degradation of pesticides at a higher level of temperatures may also result from increased volatility and photodecomposition of the molecules. These findings align with those of [26] who observed that the fungicide azoxystrobin degraded slowly and persisted in the soil for up to five months under incubation. He also reported that the biodegradation rate of the fungicide Amistar in soil incubated at 40º C was higher than in soil incubated at 18ºC. Moreover, [27] indicated that biodegradation of oxyfluorfen in soil incubated at 40ºC after 45 days of incubation ranged from (55.2-78.3%) than in soil incubated at 28ºC (17.5-36.6). [28,29] reported that half- life Benomyl–MBC was found to decrease with increased temperature from 23 to 33ºC. Working on oxyfluorfen [30,31] reported lower half- life values, at higher temperature.

The data further revealed that the application of organic and inorganic fertilizers enhanced early degradation of atrazine and reduced half-life of this herbicide. Organic fertilizers, especially those

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derived from plant resides enhanced degradation and improve soil fertility. This could possibly be due to the available carbon in organic material, which is important for the pesticide-degrading microorganisms as sources of nutrients, carbon and energy [32–34].

Generally, mineral fertilization of arable land positively affects and increases the biological productivity of various ecosystems as well as the microbial activity in soil [35–38]. The study found that the half-life of atrazine was shorter in Algeraif soil compared to Gerif soil. This could be attributed to the higher clay content,organic matter and other nutrient content [27,39,40]. This is because organic materials enhance microbial growth and activities [41–44]. Additionally, clayey soils generally exhibit greater adsorption capacity than light (sandy) soils [45–47].

Finally, the results indicated that degradation rates of atrazine were inversely proportional to concentrations. [48–50] reported similar findings, concluding that the degradation of Thiram fungicide in soil is inversely proportional to its concentration. One of the crucial factors affecting pesticide degradation is the soil's organic matter content of soil, which increases the biomass of the active microbial population and the degradation as well [46,51,52].

5. Conclusions

This study underscores the pivotal role of some abiotic factors studied in this experiment namely; NPK fertilization, soil type, temperature and residue in reducing the half-life of atrazine and promoting its degradation across different soil types. Results demonstrate that higher temperatures and the application of maize straw or NPK fertilizers significantly accelerated atrazine degradation, underscoring the synergistic influence of biological and environmental factors in mitigating pesticide persistence. Additionally, soil composition played a vital role, with Algeraif soil's higher clay and organic matter content leading to shorter atrazine half-lives compared to Gerif soil. These findings emphasize the importance of implementing tailored soil management strategies to optimize degradation and reduce environmental contamination. Based on these findings future research is recommended to focus on: (1) Long-term field studies to validate laboratory findings under natural conditions. (2) The impact of diverse microbial communities and their specific roles in pesticide degradation. (3) The interaction of additional organic amendments with soil microorganisms in various climates and soil types. (4) The broader ecological effects of enhanced atrazine degradation, particularly on non-target organisms and nutrient cycling. Such research will contribute to the development of more sustainable agricultural practices and help mitigate the environmental risks associated with pesticide use.

Author Contributions: **A.K.A.E.**: Conceptualization, Methodology, Data Curation, Writing – Original Draft, Writing – Review & Editing. **Emad H. E. Yasin**: Formal Analysis, Writing – Original Draft, Writing – Review & Editing. **Kornel Czimber**: Writing – Review & Editing. **A.G.O, M. M. and A.M.Z**: Supervision, Investigation, Formal Analysis, Writing – Original Draft, Writing – Review & Editing. **E.A.E.E.**: Supervision, Investigation, Formal Analysis, Writing – Original Draft, Writing – Review & Editing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data that support the findings of this study are available from the first author upon reasonable request.

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Conflicts of Interest: The authors declare no conflicts of interest.

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Abbreviations

The following abbreviations are used in this manuscript:

AOAC Association of Official Analytical Chemists

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