Development of a novel green waste compost stability monitoring method using the CIELAB color model

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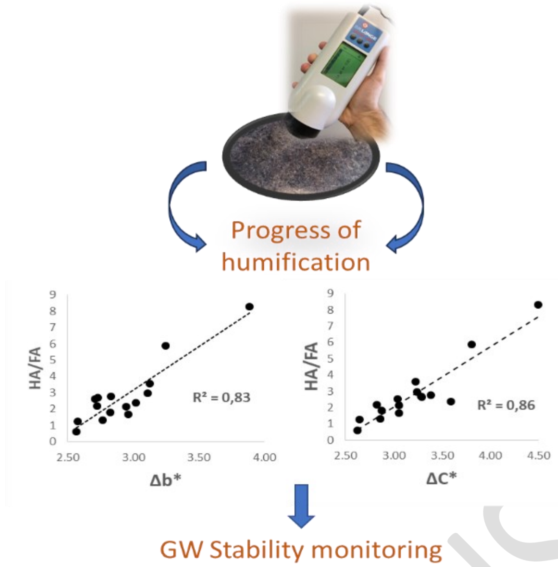
Graphical Abstract



ABSTRACT

Compost stability is an essential parameter of composting. Recent studies have shown that the color of compost is influenced by the initial characteristics of the main organic substrates. In this study, the progression of CIELAB color variables and typical compost stability and maturity indices were monitored during composting of green waste (GW) with different characteristics from previous studies. Results showed that the color variables a*, b* and C* exhibited a constant downward trend and a strong correlation with composting time ($R^2 > 0.90$). In addition, the color variables Δb* and ΔC* were found to be correlated with the humification of the compost, and in particular HA/FA with R^2 values above 0.83. Δb* and ΔC* are not affected by the initial characteristics of the green waste. Therefore, they can be used to monitor the stability of GW compost, regardless of different composting parameters, such as windrow size, additional materials, conditions, initial properties, and waste treatment delays. Δb* and ΔC* values above 2.76 and 2.96, respectively, can be used as an indicator of an acceptable degree of GW humification. Color analysis is a quick and easy compost stability monitoring method, and it can complement standard stability physicochemical indices.

Keywords: Green Waste composting, CIELAB color model; stability monitoring method

1. Introduction

Composting is a promising and integrated process used for the treatment of various organic wastes. It is the biological decomposition and stabilization of organic matter in aerobic conditions as a result of the biologically generated heat and the production of a stable product without pathogens, which can be used as fertilizer or soil amendment (Haug 2018). Composting is a discontinuous four stage process that can last from a few weeks to even months (Epstein 1997;Diaz and Savage 2007). For most agricultural applications the final product of composting must be characterized as mature and stable (CCQC 2001;Komilis and Tziouvaras 2009;Azim *et al.* 2018). Immature and unstable composting products can lead to poor plant growth and odor (Prasad *et al.* 2010), while also posing several additional problems for storage and marketing (CCQC 2001).

Compost maturity and stability are important parameters of compost quality (Prasad *et al.* 2010;Azim *et al.* 2018). Compost stability refers to the rate or degree of decomposition of organic matter, while maturity refers to the reduction of phytotoxic substances (Prasad *et al.* 2010), which is associated with the absence of damage to plants (Azim *et al.* 2018). Stability and maturity are different aspects of compost quality. In fact, stable composts may still contain phytotoxic compounds and mature composts may still have high microbial activity (Prasad *et al.* 2010). Nevertheless, it should be noted that these terms are still often used interchangeably (Brinton *et al.* 1995;Antil *et al.* 2013) in various studies, as more stable products are usually also more mature (Prasad *et al.* 2010).

The stability of compost can be evaluated using certain indices such as carbon to nitrogen ratio (C/N), humic acid to fulvic acid ratio (HA/FA) and oxygen uptake rate (Iglesias Jiménez and Pérez García 1991;Epstein 1997;CCQC 2001;Diaz and Savage 2007;Khalil *et al.* 2008;Khan *et al.* 2009;Prasad *et al.* 2010;Vlyssides *et al.* 2017;Azim *et al.* 2018). The scientific community generally uses methods based on microbial respiration. In Europe, in particular, OUR (EN 16087-1) and self-heating (Brinton *et al.* 1995) are considered valid methods for compost stability by the EU Fertiliser Products Regulation and the Joint Research Centre study (Prasad and Foster 2023). A more recent study by Prasad and Foster

(2023) proposed to retain the OUR test as a stability method while proposing new limits for compost application, in Ireland, in field/landscaping (25 mmolO2/ kg organic solids/ h) and in growing media (15 mmolO2/ kg organic solids/ h). In addition, the degree of humification is proposed in recent studies (Abdellah *et al.* 2022) for the evaluation of compost stability, as it depicts the intensity of decomposition of organic matter, and also, the nutrient content of the compost and its effect on soil properties. The application of compost with a HA/FA ratio above 1.9 is described by Antil *et al.* (2013) as more effective and sustainable for the environment and agriculture. However, it should be noted that the HA/FA values of composting products vary due to the different composition of the raw materials (Veeken *et al.* 2000).

The maturity of the compost is usually assessed based on the germination index (GI) and, less frequently, on ammonium to nitrate nitrogen ratio (N-NH4/N-NO3). The most common practice in Europe for assessing compost maturity is a certified germination test (EN 16086-2), especially when applying compost to container-grown plants (Prasad and Foster 2023). Moreover, $N\text{-}NH_4/N\text{-}NO_3$ has been reported as a less reliable maturity index if both concentrations are lower than 75 ppm (CCQC 2001).

Monitoring certain of the above chemical stability/maturity indices, especially HA/FA, usually requires costly and time-consuming analyses increasing the monitoring cost of composting (CCQC 2001). OUR, self-heating and germination tests are more rapid and relatively cheap analyses and they have been adopted by the EU Fertiliser Regulation as standard methods for assessing compost stability and maturity. In general, the germination test (EN 16086-2), the self-heating test (Brinton *et al.* 1995) and OUR (Veeken *et al.* 2003) require approximately 3, 5 and up to 5 days, respectively.

Recent studies (Khan *et al.* 2009;Tsivas *et al.* 2021;Tsivas *et al.* 2023) have shown that compost color, and in particular the CIELAB color model, could partially mitigate typical compost physicochemical analyses and provide a rapid and more cost-effective method for monitoring composting. Compost color change has been shown to follow the evolution of composting (Khan *et al.* 2009;Tsivas *et al.* 2021), and, in particular, organic matter transformation (Tsivas *et al.* 2023). In certain cases, and particularly when the composting phases are sequential (Tsivas *et al.* 2023) and do not merge (Khan *et al.* 2009;Tsivas *et* *al.* 2021), the color of compost appeared to be able to distinguish the different phases of composting. In addition, the study by Tsivas *et al.* (2023) showed that compost color had almost similar values and identical progression patterns when composting similar main organic substrates with different additives. However, the color variables appear to be influenced by the inherent properties of the raw materials (Tsivas *et al.* 2023). In particular, different composting substrates exhibit different color values during composting (Khan *et al.* 2009;Tsivas *et al.* 2021). No study has yet been published that addresses the possible influence of different initial properties of similar organic substrates on compost color.

To address this, composting experiments using green waste (GW) with different properties (collection period, windrow size, delayed treatment) from previous studies were conducted to observe the evolution of color (CIELAB color variables) along with typical stability and maturity indices and investigate whether any color variables can bypass the influence of compost color by the inherent characteristics of the raw materials. The main objective was to develop a novel colorimetric method for composting that could be used to monitor the stability and/or maturity of green waste composting regardless of the inherent characteristics of the main organic substrate.

2. Materials and methods

2.1. Materials

For this study, GW was used as the main organic substrate for composting along with various additional materials such as zeolite and mature compost. The green waste was collected in winter during seasonal municipal tree pruning in the Attica region and consisted mainly of leaves and bark. After collection GW was shredded using a wood chipper with a diameter of 2.5cm**.** Zeolite consisted of 90% clinoptilolite. Mature compost derived from previous GW composting procedures with the same added materials.

2.2. Composting process

Composting experiments began four months after GW collection and included a main process whose color and physiochemical parameters were monitored throughout the composting period and a duplicate that was used only to validate the color change progress of similar composting processes. Composting was performed according to the instructions of Tsivas *et al.* (2023). This involved the use of open windrows on an industrial scale along with gore covers under extreme weather conditions (heavy rainfalls). The composition of the compost piles is presented in Table 1. During composting additional water was added to the piles to adjust their moisture levels to 40-60%. Oxygen concentration levels were maintained at 5% in the composting pile in order to avoid anaerobic conditions (Vlyssides *et al.* 2017).

Table 1. Characteristics of the two composting experiments

Composting process	**Main**	**Duplicate**
GW (m^3)	16.0	16.0
Mature compost (m^3)	1.6	1.6
Zeolite (kg)	50.0	50.0
Moisture GW (%)	36.1	36.1

2.3.Physicochemical and color analysis of compost

During composting, 15 samples were collected, approximately once per week, following the instructions of Thompson (2001) and pretreated (e.g., drying, sieving) prior to analysis according to the procedures described by Tsivas *et al.* (2023). Physicochemical compost properties such as oxygen uptake rate (OUR), total Kjeldahl nitrogen (TKN), organic carbon (OC), pH, ammonium and nitrate nitrogen (N-NH_4, N-NO_3), humic and fulvic acids (HA, FA) and Germination Index (GI) were conducted according to the methods described by Tsivas *et al.* (2023). Compost color was measured using the CIELAB color model and a portable colorimetric device (Hach Lange LMG 183) as described by Tsivas *et al.* (2021). The specific characteristics and calculation methods of all the CIELAB color variables used in this study are listed in Table 2, adapted from Tsivas *et al.* (2021).

2.4.Regression and correlation analysis

The relationship between the CIEALAB model color variables and composting time was examined using regression analysis. The best fitting equations with the strongest correlation were selected based on the values of Pearson's correlation coefficient (R^2). Pearson's correlation coefficient (r) was used to determine the relationship between the CIELAB color variables and the physiochemical parameters of composting.

Table 2. CIELAB color variables (adapted from Tsivas *et al.* (2021))

Color variables	Description	Calculation
L^*	Perpetual Lightness range: 0 black, 100 white	Measured by Hach Lange LMG 183
ΔL^*	L^* difference	$\Delta L^* = L^*_0 - L^*_t$
a^*	Green/red opponent colors range: (-) green, (+) red	Measured by Hach Lange LMG 183
Δa^*	a^* difference	$\Delta a^* = a^*_0 - a^*_t$
b^*	Blue/yellow opponent colors vision range: (-) blue, (+) yellow	Measured by Hach Lange LMG 183
Δb^*	b^* difference	$\Delta b^* = b^*_0 - b^*_t$
C^*	Chroma	$C^* = \sqrt{a^{*2} + b^{*2}}$
ΔC^*	C^* difference	$\Delta C^* = C^*_0 - C^*_t$
h^0	Hue angle	$h^0 = tan^{-1}(a^*/b^*)$
a^*/b^*	Chromatic quotient	a^* to b^* ratio
ΔE^*	Total color difference	$\Delta E^* = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}}$

3. Results and discussion

3.1. Green Waste composting color progress

Color progression during the 102 days of composting of GW (main, duplicate) is shown in Figure 1.

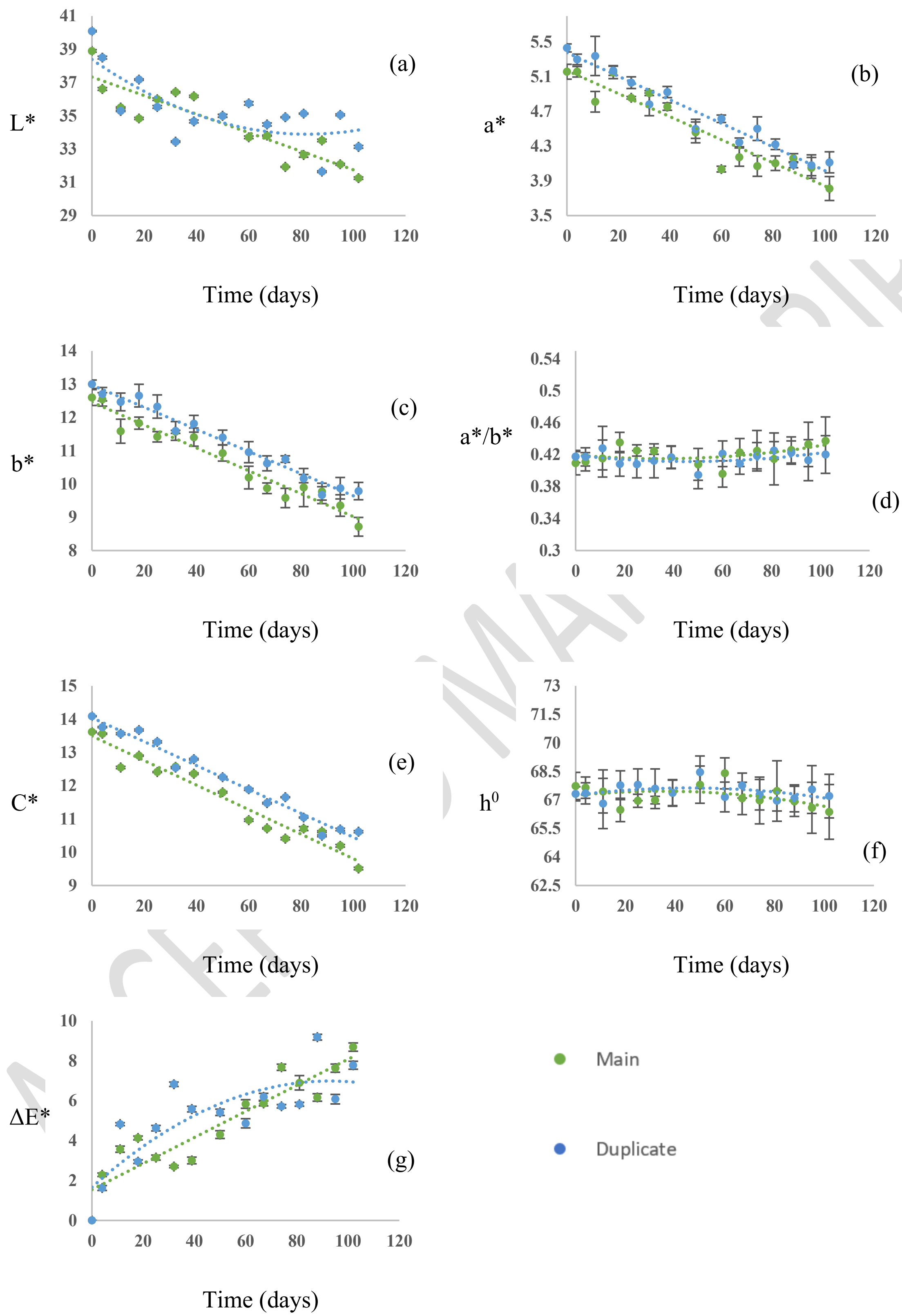


Figure 1. Green Waste composting (Main and Duplicate) color progress

The color variable L* (Figure 1a) showed a steady decreasing trend during the composting of the main experiment. In contrast, during composting of the duplicate, L* showed a rapid downward trend only during the first 11 days of composting and then stabilized with an additional downward trend on the 88th day of composting. The values of color variables a*(Figure 1b), b* (Figure 1c) and C* (Figure 1e) gradually decreased during both composting experiments until the end of the respective process. As for the color variables a*/b* (Figure 1d) and h^0 (Figure 1f) their values scatter during composting. ΔE* (Figure 1g) gradually increased during the composting process of the main experiment and showed an equally gradual increasing trend, except for a temporal stabilization of its values after 80 days, during the composting of the duplicate. The difference between the ΔE* values of the main experiment and the duplicate may be attributed to the influence of L* values, which have been shown to be a less reliable color variable for compost monitoring in previous studies (Tsivas *et al.* 2021;Tsivas *et al.* 2023).

The color of compost, as represented by the variables of the CIELAB color model, also exhibits a constant pattern of variation in previous studies. Specifically, color variables a*, b* and C* also decreased and ΔE* increased during composting of olive mill waste (Tsivas *et al.* 2021), green tea waste (Khan *et al.* 2009) and green waste (Tsivas *et al.* 2023). Based on the results of this study, the different initial properties of GW do not affect the pattern of color progression, which remains constant in all composting processes.

Chromatically, the constant downward trend of a*, b*, C* shows that the compost color in CIELAB 3D color space is constantly moving from red and yellow hues to green and blue hues. As for lightness (L*), the values are closer to black (0) than to white (100) and show a slightly decreasing trend over time for each composting experiment. These changes in color variables, mathematically, represent the evolution of compost color from light brown to dark brown.

The best fitting equations (i.e., with the highest R^2 value) describing the relationship between the color variables and composting time are listed in Table 3. Most of the color variables in the two experiments have similar fitting equations. The only exceptions are the color variable L*, and consequently, the color variable ΔE^* due to the former's involvement in the equation for determining the latter. Moreover, the color variables a^*, b^* and C^* exhibit a very strong correlation with composting time, with R^2 values greater than 0.90. ΔE^* also has an adequate correlation with composting time, with R^2 values greater than 0.80. However, the color variables a^*/b^* and h^0 do not show a strong correlation with composting time as their values show great fluctuations during composting.

The fact that both composting experiments had similar fitting equations, for almost all color variables, and also had fairly similar color values suggests that the two composting experiments performed similarly. These results once again prove that composting processes with the same main organic substrate properties have identical color change patterns, which is consistent with the data from the Tsivas *et al.* (2023) study. However, it should be noted that the color values and fitting equations of the GW composting experiments in the current study are significantly different from those reported in the previous study by Tsivas *et al.* (2023). This may be attributed to the fact that GW had different collection periods and also to the four-month delay in the application of GW in composting, which affected the initial properties of the organic substrate and thus the progress of composting, and consequently the color change pattern.

Table 3. Regression analysis of the relationship of GW compost color variables and composting time (main, duplicate)

Fitting equations (main)	R^2	Fitting equations (duplicate)	R^2
$L^* = -5.58\text{x}10^{-2}\ t + 37.33$	0.82	$L^* = 6.62\text{x}10^{-4}\ t^2 - 1.09\text{x}10^{-1}\ t + 38.39$	0.58
$a^* = -1.33\text{x}10^{-2}\ t + 5.17$	0.90	$a^* = -1.36\text{x}10^{-2}\ t + 5.38$	0.95
$b^* = -3.44\text{x}10^{-2}\ t + 12.46$	0.95	$b^* = -3.33\text{x}10^{-2}\ t + 12.97$	0.97
$h^0 = 1.87\text{x}10^{-4}\ t^2 + 1.30\text{x}10^{-2}\ t + 67.24$	0.22	$h^0 = 1.81\text{x}10^{-4}\ t^2 + 1.66\text{x}10^{-2}\ t + 67.25$	0.31
$C^* = -\ 3.69\text{x}10^{-2}\ t + 13.49$	0.95	$C^* = -3.59\text{x}10^{-2}\ t + 14.05$	0.97
$\Delta E^* = 6.54\text{x}10^{-2}\ t + 1.54$	0.85	$\Delta E^* = -6.16\text{x}10^{-4}\ t^2 + 1.15\text{x}10^{-1}\ t + 1.66$	0.68
$a^*/b^* = 3.84\text{x}10^{-6}\ t^2 - 2.66\text{x}10^{-4}\ t + 0.419$	0.22	$a^*/b^* = 3.68\text{x}10^{-6}\ t^2 - 3.38\text{x}10^{-4}\ t + 0.419$	0.02

3.2.Physicochemical parameters progression of composting

In the current study, only the physicochemical parameters of the main composting experiment were monitored during composting, which are shown in Figures 2-5. Th temperature (Figure 2a) does not reach high values above 60 ^{0}C until ten days after the start of composting and remains at a high level, above 55 ^{0}C, during the rest of composting. Therefore, in this experiment, the thermophilic stage of organic matter decomposition lasts almost the entire composting process. OC (Figure 2b) and TKN (Figure 2c) show a steady decreasing and increasing trend, respectively, until day 88 and then remain constant until the end of composting. These fluctuations are also reflected in the C/N ratio (Figure 2d), which decreases until day 88 (C/N=17.43) and then remains stable. In addition, the values of GI (Figure 4d), $N\text{-}NH_4$ (Figure 4a) and pH (Figure 3b), which represent the detoxification of the compost, show fluctuations for 60, 81 and 88 days, respectively, and then stabilize for the rest of the composting period. As composting progresses, $N\text{-}NH_4$ levels decrease from 345.64 to 33.04 mg kg^{-1}, primarily due to volatilization to NH_3 (Hao and Benke 2008), which also leads to an increase in pH. The reduction of $N\text{-}NH_4$ also leads to decrease in phytotoxicity (Tiquia 2010), as shown by the increasing GI values up to 114.20%. In addition, during composting of the main experiment, $N\text{-}NO_3$ (Figure 4b) decreases from 131.45 to 28.50 mg kg^{-1} by day 84 and then remains stable. Moreover, the gradual decrease of OUR (Figure 3a), from 79.7 to 10.5 mmol O_2 kg organic solids^{-1} h^{-1}, by day 88, indicates the existence of intense microbial activity during almost the entire composting period. Humification of the main experiment starts almost at the beginning of composting with the increase of the values of FA (Figure 5a), which reach a maximum of 69.61 mg g^{-1} four days after the beginning of composting, and continues until their decrease and the gradual increase of the HA values (Figure 5b), which reach a maximum of 114.86 mg g^{-1} at the end of the process. These results indicate that in the current study the stages of composting are intertwined and do not sequential. This fact is also reflected in the linear variation trend of the color variables a*, b*, C* and ΔE*, which was also reported in previous studies were the composting phases were also intertwined (Khan *et al.* 2009;Tsivas *et al.* 2021).

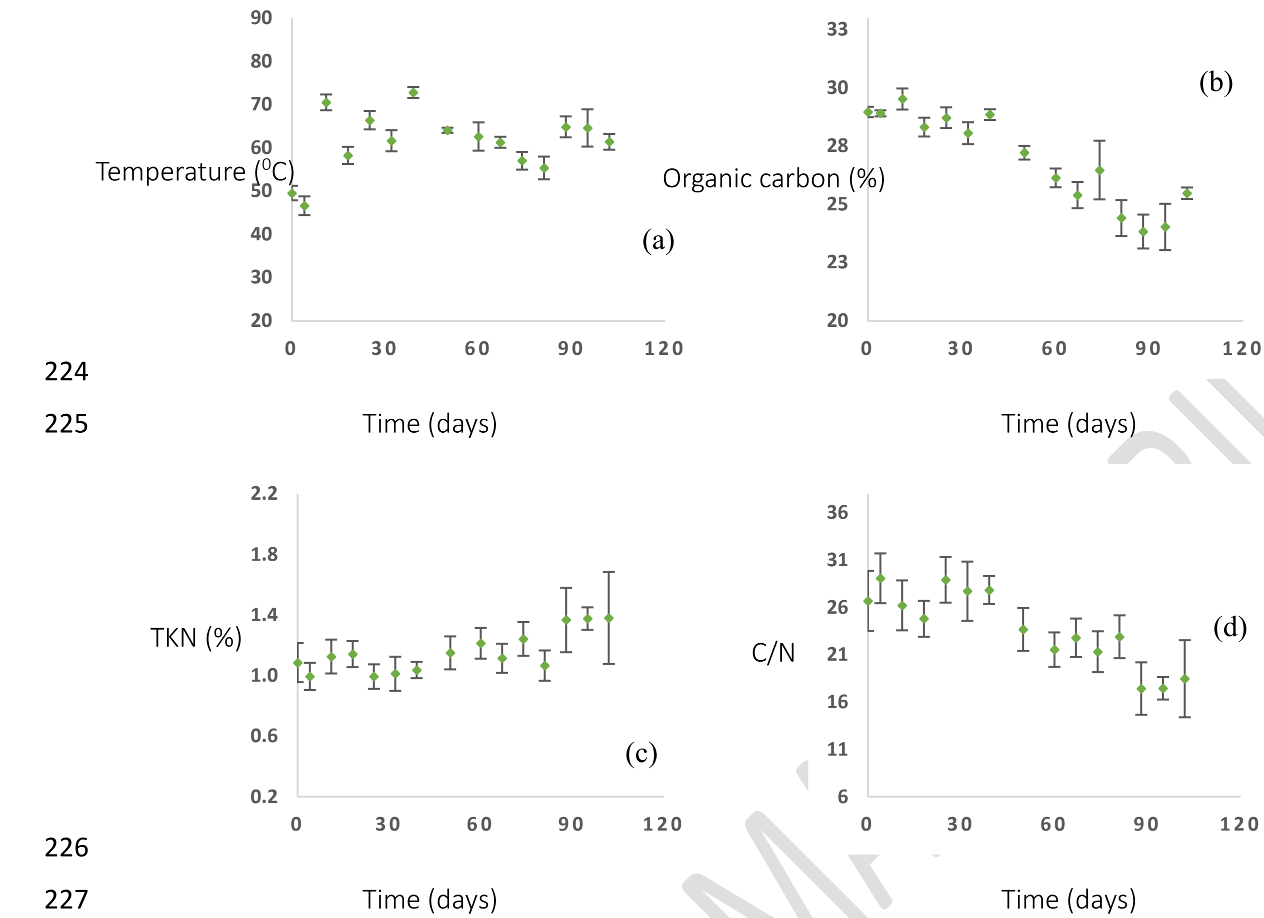


Figure 2. Temperature (a), organic carbon (b), total Kjeldahl nitrogen (c) and carbon to nitrogen ratio (d) during the main composting process

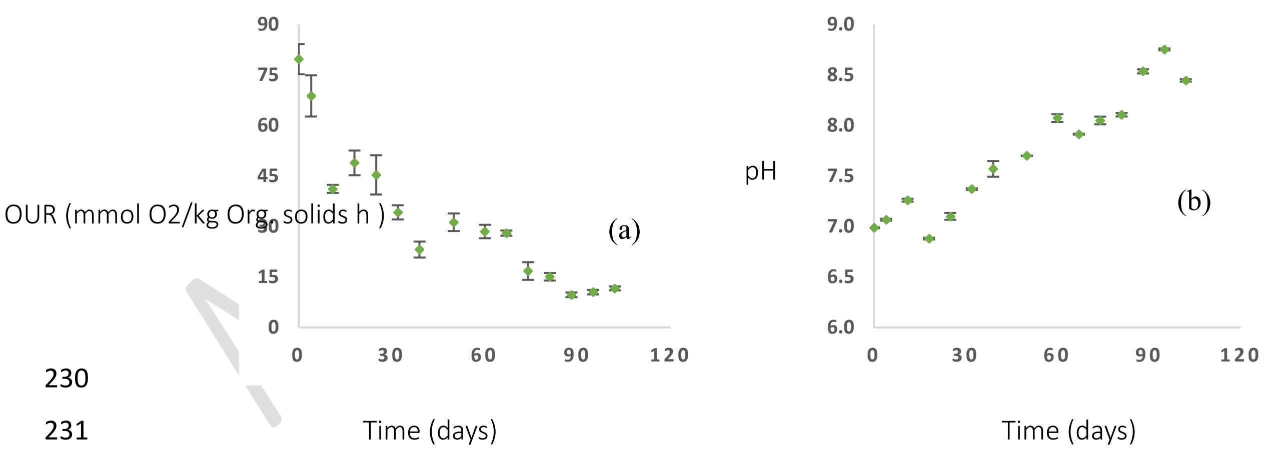


Figure 3. Oxygen uptake rate (a), pH (b) during the main composting process

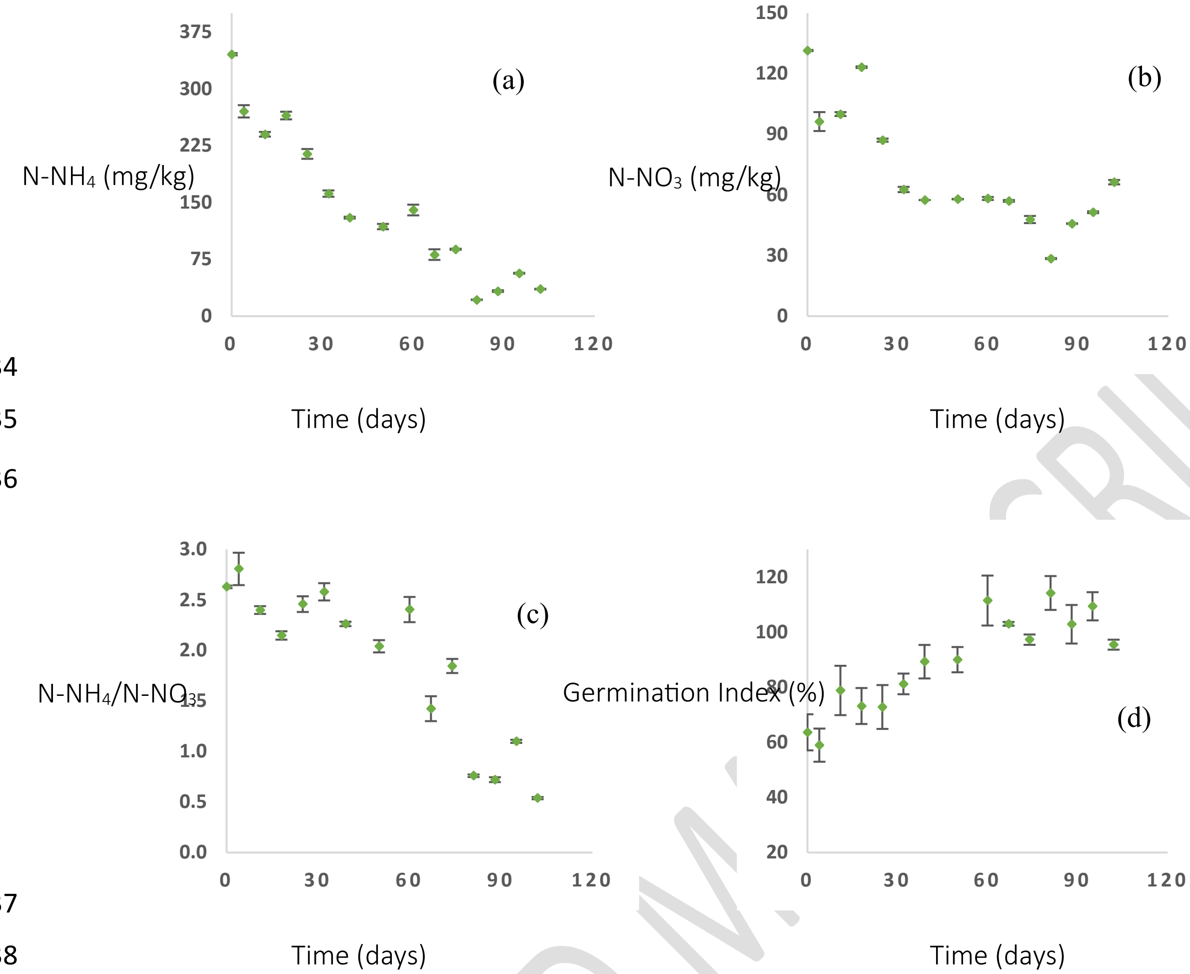
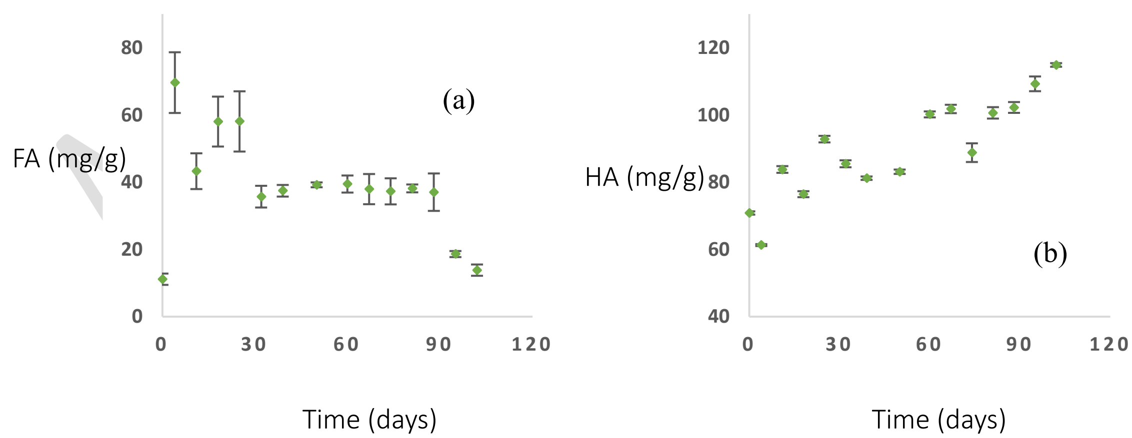


Figure 4. Ammonium nitrogen (a), nitrate nitrogen (b), ammonium to nitrate nitrogen ration (c), and Germination Index (d) during the main composting process



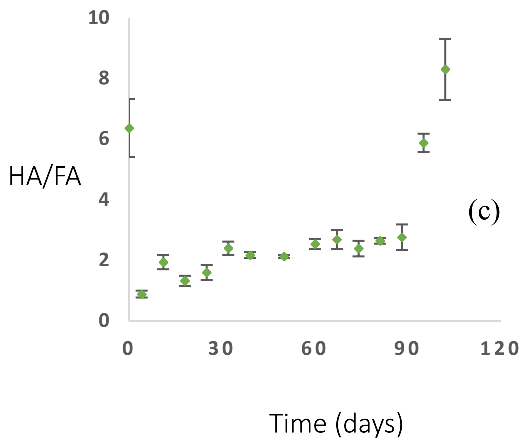


Figure 5. Fulvic acids (a), humic acids (b) and humic to fulvic acid ratio (c) during the main composting process

3.3.CIELAB color variables as indicators of compost stability and maturity

The relationship between the CIELAB color variables and the physicochemical parameters of composting measured in this study was evaluated using the Pearson correlation coefficient (r) and the results are presented in Table 4. Only the color variables a*, b* and C* were considered, as they showed a strong correlation with composting time in all GW experiments (current study, Tsivas *et al.* (2021)). Based on the r values shown in Table 4, the color variables a*, b*, C* of the main composting experiment show a very strong relationship with OC, GI, N-NH_4, N-NH_4/N-NO_3, OUR, HA and C/N and a strong relationship with N-NO_3, HA/FA and TKN, regarding the total duration of composting.

However, in previous studies on GW composting, Tsivas *et al.* (2023) observed that the color variables a*, b*, C* showed a constant decreasing nonlinear trend with fluctuations mainly related to the change of OC, C/N, HA and HA/FA. During composting of the main experiment of the current study, the formation of humic substances began four days after the start of composting, and therefore, the color variables a*, b* and C* showed a linear downward trend throughout the composting period. As for the evolution of the OUR values, which is generally used to evaluate compost stability (Prasad *et al.* 2010), color variables b* and C* in the study of Tsivas *et al.* (2023) seem to follow their decreasing trend in both composting experiments, but only to a certain extent (43-49 days), as the CIELAB values continue to decrease even after the stabilization of the OUR values. As with N-NH4/N-NO3 and GI, which are typical maturity indices (CCQC 2001;Azim *et al.* 2018;Prasad and Foster 2023), the color variables a*, b*, C* are not able to represent their progression. Only during the composting of Compost 2, do the color variables b*, C* correlate to a small extent with the progress of GI (28 days).

Table 4. Relationship of color variables a*, b*, C* with the phytochemical parameters of the main composting experiment as expressed with Pearson's correlation coefficient (r), n=15

Color variables/ Physicochemical parameters	**a***	**b***	**C***
OC	0.858*	0.869*	0.870*
GI	-0.904*	-0.863*	-0.872*
$N\text{-}NH_4/N\text{-}NO_3$	0.789*	0.855*	0.849*
$N\text{-}NH_4$	0.895*	0.910*	0.911*
$N\text{-}NO_3$	0.750*	0.750*	0.759*
OUR	0.887*	0.887*	0.885*
HA	-0.917*	-0.917*	-0.915*
FA	0.455	0.455	0.457
HA/FA	-0.768*	-0.768*	-0.759*
pH	-0.927*	-0.927*	-0.931*
TKN	-0.769*	-0.769*	-0.765*
C/N	0.875*	0.875*	0.875*

*p values < 0.01

Based on the aforementioned results, the color change of the compost constantly indicates the transformation of organic matter and the formation of humic substances during the GW composting. Previous studies have shown that the transformation of organic matter into stable humic matter fractions, and especially the degree of humification can reflect the intensity of biodegradation (Duan *et al.* 2019) and the stability of composts (de Melo *et al.* 2016). Prasad *et al.* (2010) also reported that humic acid content can be used as an indicator of compost stability. According to other studies, the formation and concentration of humic substances can reflect the nutrient content of composts and their impact on the physicochemical and biological properties of soil (Guo *et al.* 2020). Additionally, Bernal *et al.* (2009) reported that the application of compost rich in stable humic substances in soil could enhance plant growth potential.

3.4.Development of a colorimetric method for monitoring compost stability

3.4.1. Green Waste composting

The color of the compost, represented by the a*, b*, C* variables of the CIELAB color model, showed a constant pattern of progression in all composting experiments, both in the current and previous studies (Khan *et al.* 2009;Tsivas *et al.* 2021;Tsivas *et al.* 2023). Moreover, these color variables exhibited strong relationships with both composting time and certain physicochemical parameters of composting in all studies. Furthermore, if the main composting substrate has the same physicochemical properties at the beginning of composting, similar color variables and/or fitting equations describe the color progression, regardless of the different additional materials that may be included in the composting process (Tsivas *et al.* 2023). However, if certain composting variables, and especially the initial properties of the main organic substrate, change, the same color variables and equations cannot be used. Therefore, a new colorimetric index is needed, that is not affected by the initial properties of the main composting substrate and can be used to monitor the stability of GW composting.

To achieve this goal, the progression of the CIELAB color variables Δa*, Δb* and ΔC* was also measured, as shown in Figure 6. Each of these color variables represents the color difference between the initial day and a specific time point during composting (Table 2). Therefore, these color variables could potentially eliminate the influence of the initial properties of the main compost material on the color progression of the compost. Figure 6 shows the variation of the color variables Δa* Δb* and ΔC* related to the two experiments of the current study (i.e., main and duplicate) and those of the previous study by Tsivas *et al.* (2023) (Compost 1 and Compost 2).

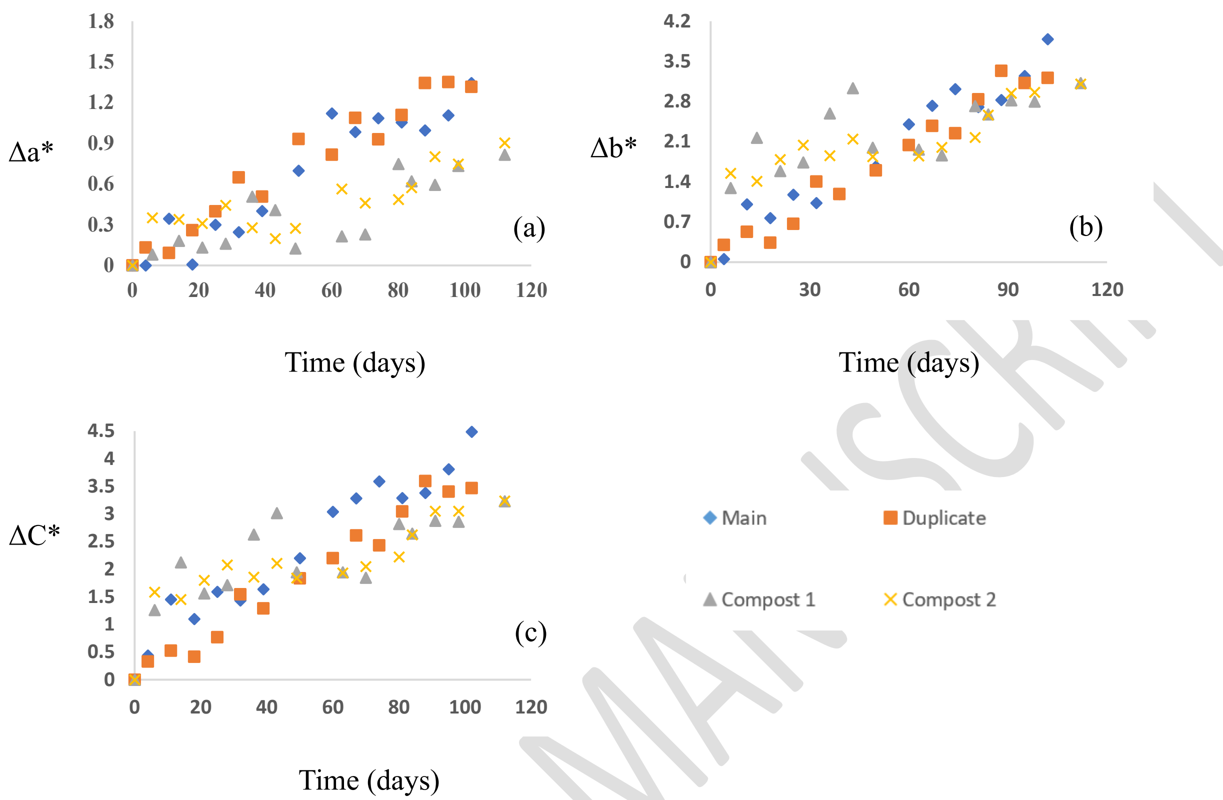


Figure 6 Impact of different collection period, added materials, windrow size and delayed treatment of GW composting on the progression of the CIELAB variables Δa*, Δb* and ΔC* (current study, Tsivas *et al.* (2023))

As shown in Figure 6, the color variables Δa* (Figure 6a), Δb* (Figure 6b) and ΔC* showed a constant increasing trend during all composting experiments. As described for the variables a*, b* and C*, the values of Δa*, Δb* and ΔC* also fluctuated depending on the decomposition of organic carbon and the formation of humic substances. In particular, a reduction in OC and an increase in HA leads to an increase in the Δa*, Δb* and ΔC* values. If this happens at the same time (i.e., OC drop and HA rise) the increase in Δa*, Δb*, ΔC* is even greater, and since, OC and HA usually progress simultaneously, it is difficult to determine the degree of their interference in the color change. After 50-60 days, all GW composting experiments showed a stronger increase in HA with a concurrent decrease in FA. After this period, the influence of HA and HA/FA on the color is more clearly visible.

To evaluate whether the color variables Δa^*, Δb^*, ΔC^* can be used to monitor the stability of GW compost, the relationship between these values with HA/FA was determined using data, from all GW experiments (current study, Tsivas *et al.* (2023)), from humification onwards as shown in Figure 7. At a certain point, the relationship between compost color and HA/FA can be described with linear equations. Δb^* and ΔC^* show the strongest correlation with HA/FA in this period, with R^2 values above 0.83. Therefore, the color variables Δb^* and ΔC^* can be used to monitor the stability of GW compost through the progression of HA/FA, regardless of different composting parameters, such as windrow size, additional materials, initial properties, and waste treatment delays. Based on the equations shown in Figure 7, Δb^* (Figure 7b) and ΔC^* (Figure 7c) values above 2.76 and 2.96, respectively, can be used as an indicator of an acceptable degree of humification (HA/FA$\geq$1.9) and the progress of compost stability. Since the color variables Δb^* and ΔC^* show a constant correlation with OUR in some but not all GW composting experiments, the proposed colorimetric method should only be used to monitor, and not to evaluate, compost stability.

The main advantage of the proposed stability monitoring method is that it is simple and fast, does not require chemicals and the results are usually ready one day after sampling (Tsivas *et al.* 2021). Standard stability analyses should be performed regularly to validate the results of the new proposed method. Since OUR and the self-heating test provide results after 5 days in some cases, the new colorimetric method could partially replace (or complement) their application, especially for day-to-day monitoring. In addition, compost producers and researchers interested in compost humification can greatly benefit from this colorimetric method, as standard assays for HA and FA analysis usually require tedious lab procedures and 2-3 days to complete the analysis.

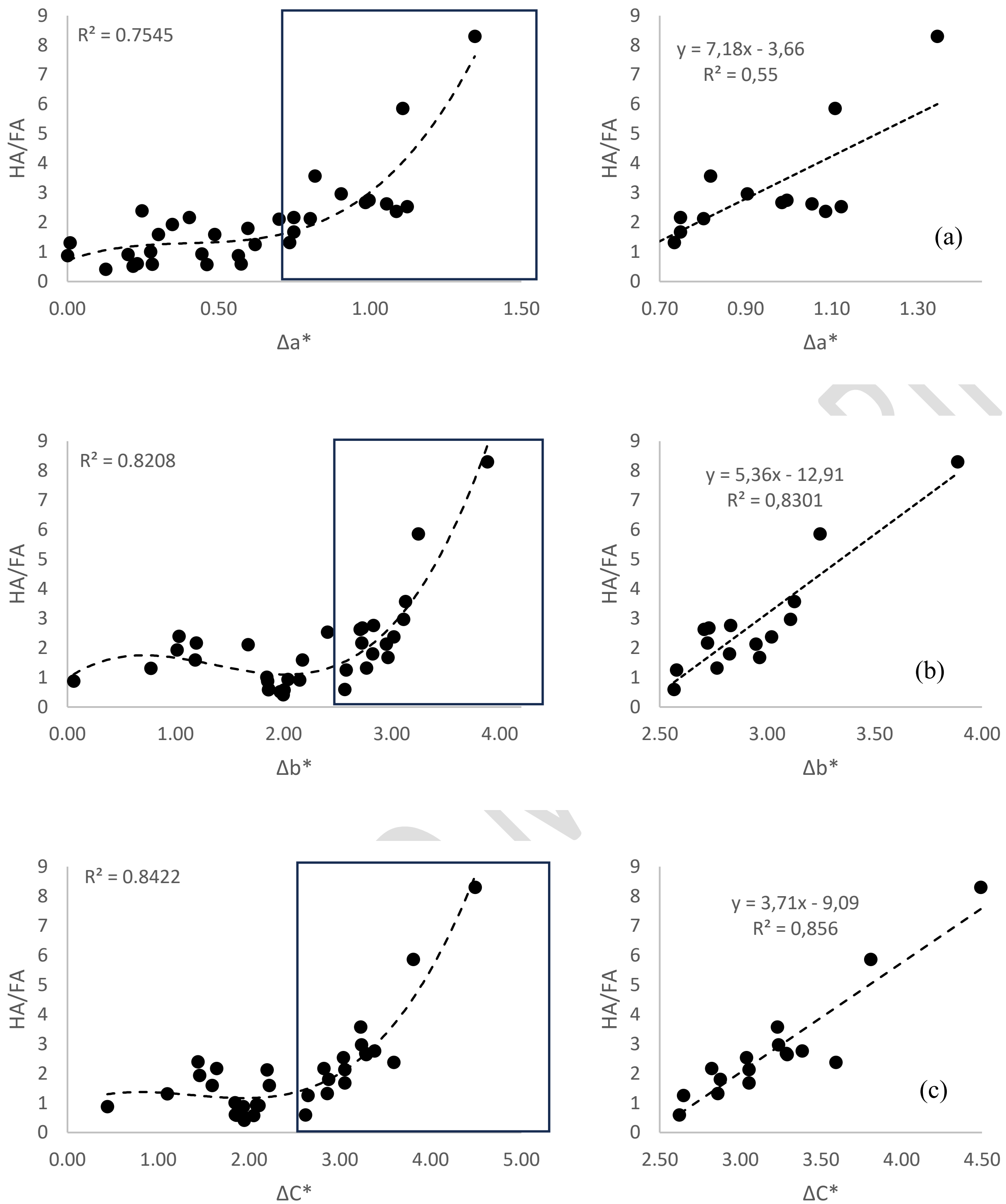


Figure 7. Relationship of the CIELAB color variables Δa*, Δb*, ΔC* with HA/FA after the initiation of humification (current study, (Tsivas *et al.* 2023))

3.4.2. Application of the proposed stability monitoring method in different organic substrates

Both in this study and in previous studies (Khan *et al.* 2009;Tsivas *et al.* 2023), it was reported that the color variables Δb* and ΔC* showed a constant upward trend during composting. In addition, it was shown that the color of compost is closely related to the humification of the organic matter. In particular, all GW composting experiments showed that an increase in Δb^* and ΔC^* values indicate the decomposition of organic matter and the increase in HA and HA/FA.

However, the composting experiments using different main organic substrates show different color value ranges. In particular, in the composting of three-phase olive pomace (Tsivas *et al.* 2021) the Δb^* and ΔC^* color variables increased from 0 to 20. Similarly, in the composting of green tea waste and rice bark (Khan *et al.* 2009), Δb^* and ΔC^* value range was greater than 14.6. Therefore, the same Δb^* color maturity value cannot be used to evaluate compost maturity of different organic wastes.

The variation of Δb^* and ΔC^* values for different organic substrates during composting is expected as the content of humic substances during composting vary due to the different composition of the raw materials (Veeken *et al.* 2000). Since the color of compost is mainly affected by the conversion of organic matter into stable humic substances, it is only natural that different organic substrates with different humic substance contents will have different values of the CIELAB color variables.

Additional research is needed to define the limits of the new proposed stability monitoring method for different organic substrates. The authors strongly believe that this new monitoring method will be able to monitor composting substrates other than GW. For example, if the Δb^* and ΔC^* values of the compost increase, this is an indication that the formation of humic substances is still in progress and that the decomposition of organic matter has not yet stabilized. In any case, all ranges, and values of Δb^* and ΔC^* need to be determined and recorded. The formation of a global database containing the progress of CIELAB variables and critical stability parameters for different composting substrates will help the scientific community to further investigate the correlation of color with composting stability.

4. Conclusions

The Δb^* and ΔC^* color variable can be used to monitor the stability of GW composting, and especially the degree of humification, independent of different composting parameters. In particular, the Δb^* and ΔC^* values not affected by the additional materials, pile size, collection time and composting delays.

However, the same Δb^* and ΔC^* values cannot be used to evaluate compost maturity for all composting processes because these values are different for each organic substrate. The proposed novel color method for monitoring compost stability, based on Δb^* and ΔC^* values, offers a reduction in composting analysis time and complexity, as it is a quick and easy compost stability monitoring method, and it can complement standard stability physicochemical indices.

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