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Effect of pH and temperature on the biodegradation of oxytetracycline, streptomycin, and validamycin A in soil

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Abstract

Residual antibiotics in agricultural soils can be of concern due to the development of antibiotic resistant microorganisms. Among various antibiotics, oxytetracycline (OTC), streptomycin (ST), and validamycin A (VA) have been used for agricultural purposes in South Korea; however, studies on the biodegradation of these antibiotics in soil are limited. Therefore, this study investigated the effects of pH (5.5, 6.8, and 7.4) and temperature (1.8, 23.0, and 31.2 °C) conditions on the biodegradation of these antibiotics in soil. The biodegradation tests were carried out in the field soil (FS) and rice paddy soil (RS) for 30 d with OTC and ST and 10 d with VA, and the residual antibiotics concentrations were monitored over the degradation period. Under various conditions, the degradation rates of ST was lower (11–69%) than that of OTC (60–90%) and VA (15–96%). The degradation half-lives of OTC and VA tend to decrease with increasing pH value, while the degradation half-life of ST tend to increase with increasing pH value. But, the effect of soil pH on the antibiotics degradation was not statistically significant, except for ST in the FS and RS and VA in the FS. The degradation of three antibiotics was greater at higher temperatures (23.0 °C and 31.2 °C) than at lower temperature (1.8 °C), and the degradation half-lives decreased with increasing temperature. The different degradation characteristics of different antibiotics in soil can be explained by the different characteristics of the antibiotics (e.g., sorption affinity, chemical forms) and soil (e.g., organic matter content). The results suggest that the degradation characteristics of antibiotics need to be considered in order to properly manage the residual antibiotics in soil.

Keywords Biodegradation, Oxytetracycline, pH, Streptomycin, Temperature, Validamycin A

Introduction

Various antibiotics have been used in agricultural and livestock industries and their uses have been continuously increasing [1]. Among various antibiotics, tetracycline antibiotics [e.g., tetracycline, oxytetracycline (OTC)] and aminoglycoside antibiotics [e.g., streptomycin (ST), validamycin A (VA)] are commonly used antibiotics. In South Korea, tetracycline antibiotics are the most used antibiotics and OTC is the most used antibiotic among the different tetracycline antibiotics [2]. The increasing uses of antibiotics are of concern because of the development of antibiotic resistant microorganisms and antibiotic resistance genes in the environment [3, 4]. When antibiotics are introduced to the soil environment through various routes, they can have adverse effects on soil organisms including crops grown in soil [5]. The residual antibiotics in the soil environment can be degraded by natural processes such as photodegradation and biodegradation [6, 7]. In a previous study, a faster degradation of OTC in the OTC-contaminated soil was observed when irradiated with light [6]. Also, in the presence of light, the half-life of the ST was reduced from

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40.8 min in the absence of a catalyst (i.e., TiO_2) to 4.6 min in the presence of TiO_2 [7].

The biodegradation of antibiotics in the soil environment can be affected by various environmental factors such as chemical structure of antibiotics, properties of antibiotics, and soil properties (e.g., pH, temperature, texture, organic carbon content) [4, 8]. For example, the biodegradation half-lives of erythromycin under aerobic and anaerobic conditions were 6.4 d and 11.0 d, respectively [9]. Also, the biodegradation half-lives of deltamethrin in soil with different soil textures were different (i.e., 71.9 d for sandy soil, 68.8 d for sandy loam soil, 86.4 d for silty loam soil, and 105.3 d for silty soil) [10], The biodegradation half-life of sulfamethoxazole in soil was also affected by temperature (i.e., 20.69 d at 7.5 °C and 4.31 d at 25 °C) [11]. The biodegradation half-lives of OTC in soil were also affected by how the antibiotics were introduced to the soil [12]. When OTC was added to soil by applying the manure containing antibiotics, the half-life was 12.81 d, but the half-life was increased to 16.66 d when OTC was added to soil by spiking the antibiotic-free animal manure with OTC and to 18.89 d when OTC was directly added to soil [12]. The increased pH, electrical conductivity, enzyme activity, biomass carbon, and biomass nitrogen with the addition of manure can partially explain the faster OTC degradation in soil [12]. Furthermore, the biodegradation of antibiotics in soil can be affected by the presence of antibiotics-degrading bacteria [10, 13]. The degradation of sulfachloropyridine in soil was faster in the unsterilized soil than in the sterilized soil, suggesting that the main mechanism of the sulfachloropyridine removal was biodegradation [13]. Also, the degradation of deltamethrin by naturally occurring indigenous microorganisms in soil was slower than that in the soil bioaugmented with the deltamethrin-degrading bacteria [10].

Among various antibiotics, OTC, ST, and VA are registered as agricultural antibiotics that can be used to crops in South Korea. Previous studies on the degradation of OTC focused mostly on the photodegradation of antibiotics under different environmental conditions (e.g., initial concentration, pH, dissolved organic matter, NO_3^-, carbonate, biocarbonate) [14–16]. Previous studies on the degradation of ST and VA in soil, in particular, biodegradation of ST and VA is limited to isolation of ST- or VA-degrading microorganisms [17–19]. Thus, there is a lack of information on the biodegradation characteristics (i.e., half-lives) of OTC, ST, and VA in soil under different environmental conditions, while such information is important for proper management antibiotics in soil. Therefore, this study is set to investigate the biodegradation of OTC, ST, and VA in soil under different pH and temperature conditions.

Materials and methods

Chemicals and materials

The standard chemical for OTC hydrochloride (> 95.0%) was purchased from Tokyo Chemical Industry (Nihonbashi-honcho, Chuo-ku, Japan) and the standard chemicals for VA (PESTANAL®, analytical standard) and streptomycin sulfate salt (79.8%) were purchased from Sigma-Aldrich (Munich, Germany). Also, the agricultural antibiotic products were purchased to use for soil contamination. Okcycline (OTC 34%), Barimun (VA 5%), and Agrepto (ST 20%) were purchased from Hanearl Science (Gangwondo, South Korea), Nonghyup Chemical (Gyeonggido, South Korea), and Kyungnong (Seoul, South Korea), respectively. Acetonitrile (HPLC grade) and methanol (HPLC grade) were purchased from Honeywell Burdick & Jackson (Charlotte, USA). Water (HPLC grade) was purchased from J. T. Baker (Phillipsburg, NJ, USA). Formic acid (85%) was purchased from Samchun Chemical Co., Ltd. (Seoul, South Korea).

Soil preparation

Field soil (FS) collected from the chive growing field in D city (35.2538° N, 126.8894° E, South Korea) and rice paddy soil (RS) collected from G city (35.1730° N, 126.8985° E, South Korea) were used in this study. The soil samples were collected before sowing. The collected soils were air-dried and sieved through a 2 mm sieve. The FS consists of 25% clay, 50% silt, and 25% sand (i.e., silt loam) and the total organic carbon (TOC) content, cation exchange capacity (CEC), and pH were 4.18%, 9.33 cmol kg^{-1}, and 6.7, respectively. The RS consists of 22% clay, 41% silt, and 37% sand (i.e., loam) and the TOC content, CEC, and pH were 2.47%, 8.20 cmol kg^{-1}, and 6.2, respectively. The soil texture was measured by using the hydrometer method (USDA-SSIR 51) [20]. The TOC and CEC were analyzed by the National Instrumentation Center for Environmental Management (Seoul, South Korea) using the Walkley-Black method and ammonium acetate method, respectively. The soil pH was measured by using the pH meter (Orion Star™ A329, Thermo Scientific, USA). The FS and RS soil samples contaminated with each of three different agricultural antibiotics were prepared to use in the biodegradation tests. The initial concentrations of OTC-, VA-, and ST-contaminated soil samples were 6.0 ± 1.8 mg kg^{-1}, 8.5 ± 0.8 mg kg^{-1}, and 6.9 ± 1.3 mg kg^{-1}, respectively.

Biodegradation experimental setup

Each of the contaminated FS and RS soil samples (100 g) was placed in a 250 mL beaker (glass for OTC, polypropylene for VA and ST) and the soil moisture content was adjusted to about 60% of the soil water holding capacity. The prepared beakers were covered with parafilm to prevent water evaporation during the biodegradation period. To study the effect of soil pH on the degradation of antibiotics, three different pH conditions (i.e., 5.5 ± 0.2, 6.8 ± 0.1, 7.4 ± 0.2) were used at 23.3 ± 1.6 °C. The soil pH was adjusted with $Al_2(SO_4)_3$ and $CaCO_3$. To study the effect of soil temperature on the degradation of antibiotics, three different temperature conditions (i.e., 1.8 ± 1.0 °C, 23.0 ± 1.6 °C, 31.2 ± 1.3 °C) were used at soil pH of 6.8 ± 0.1. The three temperatures of 1.8 ± 1.0 °C, 23.0 ± 1.6 °C, and 31.2 ± 1.3 °C were selected based on the last 10 year temperature data in South Korea, to simulate winter, summer, and hotter summer temperatures, respectively. With OTC and ST, the biodegradation test was run for 30 d, while the test was run for 10 d with VA. The soil samples for each condition were prepared in triplicates.

Analysis of residual antibiotics in soil

The residual OTC concentrations in the soil samples were extracted using methanol with 9% formic acid, and the extracts were purified using a dispersive kit (Kriat QuEChERS dispersive kit E202, Korea Research Institute of Analytical Technology, Daejeon, South Korea) and filtered through a nylon filter (0.22 μm pore size) for analysis using liquid chromatography-tandem mass spectrometry (AB SCIEX triple-quadrupole mass spectrometer 4500, AB Sciex LLC, Framingham, MA 01701 U.S.A.). The residual VA and ST concentrations in the soil samples were extracted using methanol/water (50/50, v/v) containing 9% formic acid. Then, a mixture of NaCl (2 g), citric acid trisodium salt dehydrate (1 g), sodium citrate dibasic sesquihydrate (0.5 g), and formic acid (500 μL) was used to further extract the sample. The supernatant was then purified using the dispersive kit and filtered through a nylon filter (0.22 μm pore size) for analysis using LC-MS/MS. The OTC in the extracts was analyzed using a YMC-Pack Pro C18 RS column (3.0 mm I.D x 100 mm L, 3 μm particle size) using 0.1% formic acid in water and 0.1% formic acid in acetonitrile as mobile phases. The ST in the extracts was analyzed using a XBridge Amide column (4.6 I.D. x 150 mm L, 3.5 μm particle size) using 0.1% formic acid in water and 0.1% formic acid in acetonitrile as mobile phases. The VA in the extract was analyzed using a XBridge Amide column (2.1 I.D. x 150 mm L, 3.5 μm particle size) using 0.1% formic acid in water and 0.1% formic acid in acetonitrile as mobile phases.

Statistical analysis

The analysis of the statistically significant difference between the antibiotics degradation under different conditions was carried out with the GraphPad Prism software (v8.0.1, GraphPad Software, Boston, USA). The one-way analysis of variance (i.e., one-way ANOVA) was used to compare the data and the Tukey test was carried out as a post-hoc test. The data were considered to be statistically significantly different when the p value was < 0.05 at the 95% confidence level [21].

Results and discussion

Effect of soil pH on the biodegradation of agricultural antibiotics

Figure 1 shows the removal rates of the three antibiotics in the FS and RS. During the 30 d-degradation period, the OTC removal rates were 65–77%, on average, in the FS, while they were 81–84%, on average, in the RS (Fig. 1a). With both soils, the OTC removal rates after 30 d-degradation were statistically similar regardless of the soil pH condition (p value > 0.05) (Fig. 1a). Also, the OTC removal rates were not statistically different between the FS and RS (p value > 0.05) (Fig. 1a). Table 1 shows the half-lives of the three antibiotics under the different conditions used in this study. The half-lives for OTC ranged from 3.5 d to 5.0 d regardless of the soil type and pH conditions (Table 1). Although not statistically significant (Fig. 1a), the estimated half-lives of OTC in the FS (i.e., 4.0–5.0 d) seem to be longer than that in the RS (i.e., 3.5–3.8 d), and this can be attributed to the different TOC of the FS (i.e., 4.18%) and RS (i.e., 2.47%). Similarly, previous studies reported that the soil pH can affect the sorption ability of OTC on soil, and this can influence the OTC biodegradation in soil [22–24]. For example, the OTC sorption on clay decreased with increasing pH and this can be affected by the presence of cations [22]. Similarly, the sorption of tetracycline on clay was greater at pH 5 than pH 8 [23]. Tetracycline antibiotics are in cationic form at acidic pH conditions and are relatively stable, thus, more antibiotics can adsorb on negatively charged soil particles [22, 25]. OTC can be present in four different ion species (i.e., H_3OTC^+, H_2OTC, HOC^-, OTC_2^-) depending on pH [15, 26]. The chemical forms of antibiotics and the soil charges at different pH conditions can, thus, affect the sorption of antibiotics on soil. Also, desorption of antibiotics can be affected and more desorption occurs in soil having high pH conditions and low organic matter contents [24]. These sorption and desorption characteristics may lead to different degradation half-lives in soils having different pH conditions. A previous study reported the OTC half-life of 18.9 d at pH 7.3 [12], which was greater than the estimated half-lives in this study (i.e., faster degradation observed in this study). In another study, the OTC degradation of about 56% took 28 d in sandy soil at pH 5.9 [27]. Although previous studies reported that the OTC adsorption and desorption as well as biodegradation are likely to be affected by the soil pH, the results of this study showed that the

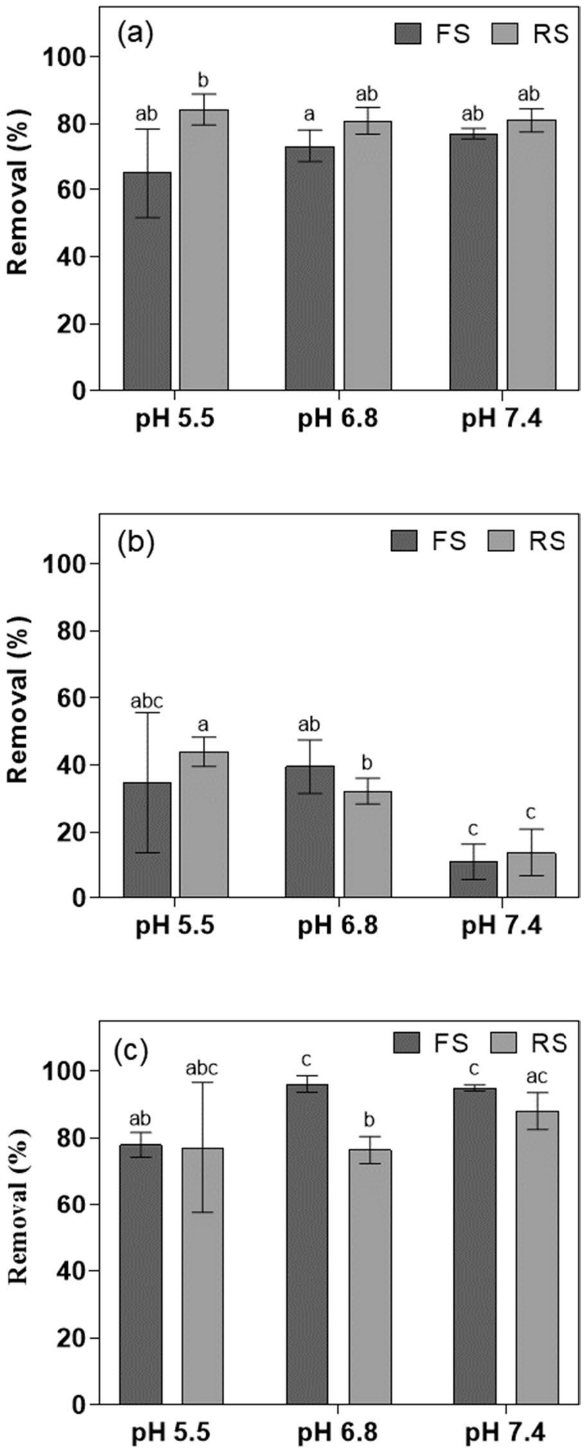

Fig. 1 Effect of soil pH on the biodegradation of **a** oxytetracycline (30 d degradation), **b** streptomycin (30 d degradation), and **c** validamycin A (10 d degradation) in the field soil (FS) and rice paddy soil (RS) at 23.0 ± 1.6 °C. Different letters indicate statistically significant differences (*p* value < 0.05)

Table 1 Effect of soil pH on the degradation rates and half-lives of oxytetracycline (OTC), streptomycin (ST), and validamycin A (VA) in field soil (FS) and rice paddy soil (RS) at 23.0 ± 1.6 °C

Antibiotics	Soil	pH	Degradation rate (d^{-1})	Half-life (d)
OTC	FS	5.5 ± 0.2	0.0705 ± 0.0097	4.8
		6.8 ± 0.1	0.0828 ± 0.0084	4.0
		7.4 ± 0.2	0.0829 ± 0.0117	4.1
	RS	5.5 ± 0.2	0.0997 ± 0.0130	3.5
		6.8 ± 0.1	0.0802 ± 0.0045	3.8
		7.4 ± 0.2	0.0898 ± 0.0114	3.7
ST	FS	5.5 ± 0.2	0.0054 ± 0.0052	22.1
		6.8 ± 0.1	0.0062 ± 0.0041	25.6
		7.4 ± 0.2	0.0016 ± 0.0015	169.4
	RS	5.5 ± 0.2	0.0074 ± 0.0017	33.5
		6.8 ± 0.1	0.0055 ± 0.0009	51.5
		7.4 ± 0.2	0.0022 ± 0.0011	143.4
VA	FS	5.5 ± 0.2	0.0808 ± 0.0095	4.0
		6.8 ± 0.1	0.1441 ± 0.0111	2.4
		7.4 ± 0.2	0.1365 ± 0.0076	2.1
	RS	5.5 ± 0.2	0.0599 ± 0.0128	5.5
		6.8 ± 0.1	0.0535 ± 0.0059	5.4
		7.4 ± 0.2	0.0897 ± 0.0073	3.5

OTC degradation was not affected by the soil pH conditions used in this study.

Figure 1b shows the ST removal rates in the FS and RS. During the 30 d-degradation period, the ST removal rates ranged from 11 to 44% depending on the soil type and pH conditions (Fig. 1b). The ST removals were statistically similar in both soils at the same pH condition (Fig. 1b); however, the half-lives were shorter in the FS than in the RS at pH 5.5 and 6.8 (Table 1). At pH 7.4, the ST removals were lower than that at other pH conditions (Fig. 1b), and the half-lives were significantly longer (i.e., 6.6–7.7 times longer for the FS and 2.8–4.3 times longer for the RS) (Table 1). With the both soils, the half-lives increased with increasing pH conditions (Table 1). Among the three antibiotics used in this study, the ST removal was the lowest, and this can be explained by its stronger sorption affinity on soil than other antibiotics such as OTC, chlortetracycline, tylosin, and erythromycin [28]. Also, ST is relatively stable from hydrolysis at the pH range of 3–8 at 28 °C [29]. A previous study did not observe any ST degradation within 30 d in the sandy loam soil treated with manure (pH 6.1) [30]. ST can also be present in four different states (i.e., ST-H_3^{3+}, ST-H_2^{2+}, ST-H^+, ST^0), and ST-H_3^{3+}, which is the main ion at pH < 6, transforms into ST-H_2^{2+} at pH 8

[31]. This leads to decreased ST sorption on soil at pH > 8 since soil is negatively charged [31]. Such changes in the ST sorption at different pH conditions can affect the degradation of ST. The biodegradation of ST can be improved by bioaugmenting with ST-degrading microorganisms. For example, a previous study observed that the degradation of gentamicin, one of aminoglycoside antibiotics, by gentamicin-degrading microorganism at different initial pH conditions (i.e., pH 5, 6, 7, 8, 9, and 10) after 7 d was similarly high (i.e., ~90%) [32]. Interestingly, the pH of the medium where the degradation took the place was changed closer to a slightly acidic condition (i.e., 6.0–6.5) regardless of the initial medium pH values [32].

Figure 1c shows the VA removals in the FS and RS. Compared to the other antibiotics, the VA removal was faster (Fig. 1c). With the FS, the VA removals were significantly greater at pH 6.8 (96%) and pH 7.4 (95%) than at pH 5.5 (78%) (p value < 0.05) (Fig. 1c). On the other hand, the VA removal in the RS were statistically similar regardless of the pH conditions (76–88%, on average) (p value > 0.05) (Fig. 1c). The half-lives of VA tend to decrease with increasing pH conditions, and they were shorter for the FS (i.e., 2.1–4.0 d) than the RS (3.5–5.5 d) (Table 1). Previous studies reported that the optimum pH range for the VA-degrading bacteria such as *Pseudomonas* sp. HZ519 and *Flavobacterium saccharophilum* is 7.1–8.0 [19, 33]. This may explain the greater VA degradation tendency at pH 7.4 than at the other pH conditions used in this study. VA is hydrolyzed first into validoxylamine A, which is then degraded into valienamine and validamine [34]. The VA degradation by *Pseudomonas* sp. HZ519 led to the formation of valienamine, and its production increased with increasing pH from 5 to 8 [19].

Effect of soil temperature on the biodegradation of agricultural antibiotics

Figure 2 shows the effect of temperature on the antibiotics removal. With both the FS and RS, the OTC removal increased with increasing temperature (Fig. 2a). For example, the OTC removal increased from 60% at 1.8 °C to 87% at 31.2 ℃ in the FS (i.e., 45% increase), while it increased from 50% at 1.8 °C to 90% at 31.2℃ in the RS (i.e., 80% increase) (Fig. 2a). The OTC removal at each temperature was statistically similar in the FS and RS (Fig. 2a). The OTC degradation half-lives decreased by about 37% from 5.9 d at 1.8 °C to 3.7 d at 31.2 ℃ in the FS

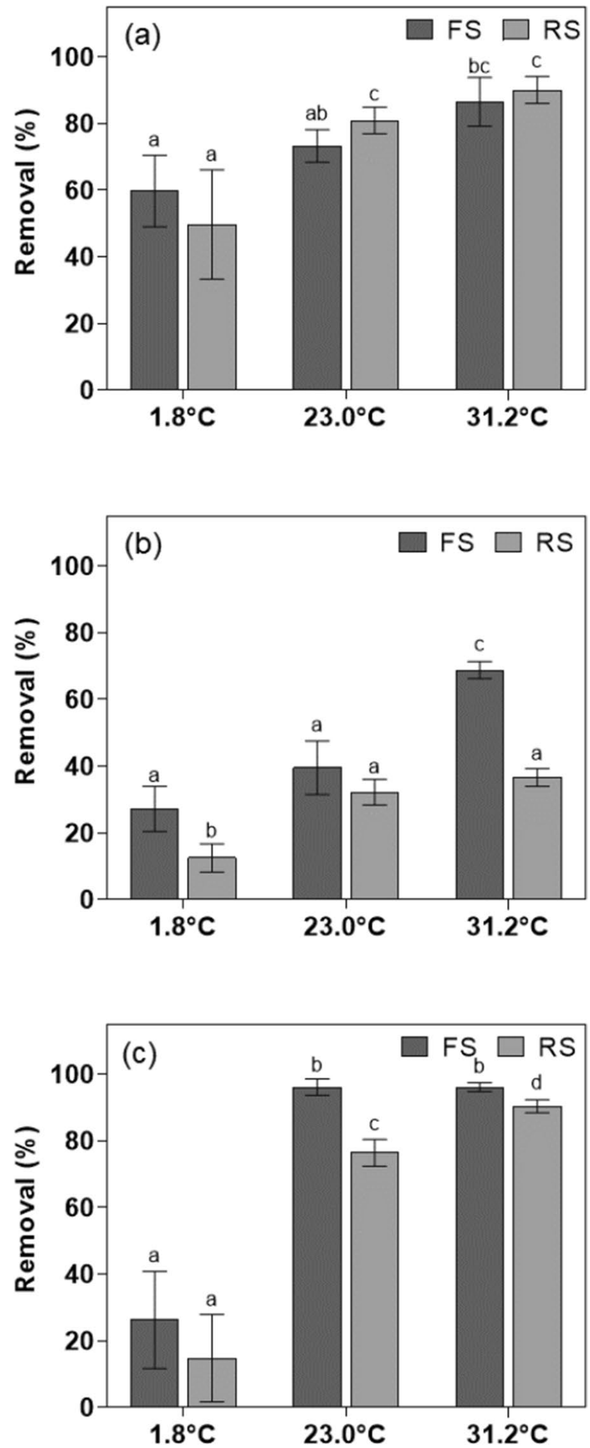

Fig. 2 Effect of soil temperature on the biodegradation of **a** oxytetracycline, **b** streptomycin, and **c** validamycin A in field soil (FS) and rice paddy soil (RS) at pH 6.8 ± 0.1. Different letters indicate statistically significant differences (p value < 0.05)

Table 2 Effect of soil temperature on the degradation rates and half-lives of oxytetracycline (OTC), streptomycin (ST), and validamycin A (VA) in field soil (FS) and rice paddy soil (RS) at pH 6.8 ± 0.1

Antibiotic	Soil	Temperature (°C)	Degradation rate (d^{-1})	Half-life (d)
OTC	FS	1.8 ± 1.0	0.0557 ± 0.0091	5.9
		23.0 ± 1.6	0.0828 ± 0.0084	4.0
		31.2 ± 1.3	0.0910 ± 0.0112	3.7
	RS	1.8 ± 1.0	0.0454 ± 0.0083	6.7
		23.0 ± 1.6	0.0802 ± 0.0045	3.8
		31.2 ± 1.3	0.0980 ± 0.0071	3.2
ST	FS	1.8 ± 1.0	0.0051 ± 0.0024	55.9
		23.0 ± 1.6	0.0062 ± 0.0041	25.6
		31.2 ± 1.3	0.0157 ± 0.0036	13.0
	RS	1.8 ± 1.0	0.0017 ± 0.0036	214.8
		23.0 ± 1.6	0.0055 ± 0.0009	51.5
		31.2 ± 1.3	0.0070 ± 0.0022	37.3
VA	FS	1.8 ± 1.0	0.0089 ± 0.0042	35.4
		23.0 ± 1.6	0.1441 ± 0.0111	2.4
		31.2 ± 1.3	0.1532 ± 0.0109	1.5
	RS	1.8 ± 1.0	0.0036 ± 0.0035	74.2
		23.0 ± 1.6	0.0535 ± 0.0059	5.4
		31.2 ± 1.3	0.0976 ± 0.0054	2.8

and the similar trend was observed with the RS (Table 2). Similarly, the OTC degradation by *Burkholderia cepacia* increased from 69.6 to 85.1% with increasing temperature from 23 to 38 ℃ [35]. Also, the OTC degradation in water by *Pseudomonas* species increased from about 20–25% to 55% with increasing temperature from 25 to 40 ℃ [36]. The chlortetracycline removal was also increased from 0% at 4 °C to 12% at 20 °C, and further increase in temperature to 30 °C led to the removal of 56% [30]. The information on the effect of temperature on the OTC degradation half-life in soil is hardly reported, while that in water has been reported. For example, the OTC degradation half-life decreased from 80 d at 4 °C to 12 d at 20 °C in lagoon water where there were mixtures of antibiotics including OTC [37]. Also, the OTC degradation half-life increased from 6.0 h at 50 °C to 66 h at 25 °C, and then to 158 h at 10 °C in water (pH 7) [38]. The half-lives of OTC decreased from 120 to 0.15 d with increasing temperature from 4 to 60 °C in the pH 9.06 buffer solution [39]. Furthermore, the OTC degradation half-life in an aqueous buffer (pH 7) was 9.4 d, and OTC degradation was faster than the other antibiotics [i.e., ceftiofur (49 d), florfenicol (> 416 d), sulfamethoxazole (> 416 d), tylosin (> 416 d)] [40].

Figure 2b shows the ST removal at different temperatures. The ST removal was increased by 156% (i.e., from 27 to 69%) in the FS with increasing temperature from 1.8 to 31.2 °C, while it was increased by 185% (i.e., from 13 to 37%) in the RS (Fig. 2b). The ST degradation half-life showed a decreasing trend with increasing temperature in both soils (Table 2). Similarly, the ST hydrolysis half-life was decreased with increasing temperature regardless of the pH conditions [29]. For example, it was decreased from 1200 h at 7 °C to 8 h at 50 °C in a pH 0.8 solution, from stable at 7 °C to 4600 h at 50 °C in a pH 5.5 solution, and from 3000 h at 7 °C to 28 h at 50 °C in a pH 9.5 solution [29]. Also, the ST degradation half-life in water (pH 7) was decreased from 105 d at 15 °C to 42.3 d at 25 °C, and to 27.5 d at 40 °C [41]. The half-lives in the RS were 2.0–3.8 times longer than that in the FS (Table 2). For example, at 1.8 ℃, the half-life in the RS was about 3.8 times longer than that in the FS (Table 2). The ST removal was lower in the RS than in the FS at the same temperature, and this can be attributed to higher TOC, which can promote microbial activity at higher temperature than lower temperature, since organic matter is likely to be degraded faster at higher temperature. Similarly, the degradation of kanamycin A, one of the aminoglycoside antibiotics, in the soil having higher OC and organic matter contents (i.e., 1.44%, 24.67 g kg^{-1}) resulted in greater kanamycin A degradation than in the soil having relatively lower OC and organic matter contents (i.e., 1.03%, 14.13 g kg^{-1}) [42]. When compared to the OTC removal, the effect of temperature on the ST removal was greater, although the total removal rates were relatively lower for ST (13–69%) than for OTC (50–90%) (Fig. 2a, b). This can be attributed to the stronger sorption affinity of ST than OTC [28].

Figure 2c shows the effect of temperature on the VA removal in soil. The VA removals were about 26% and 15% in the FS and RS, respectively, at 1.8 ℃, and they were significantly increased to 95–96% for the FS and 76–90% for the RS at higher temperatures (Fig. 2c). The half-lives for VA were also decreased from 35.4–74.2 d at 1.8℃ to 1.5–5.4 d at higher temperatures (Table 2). Previous studies reported that VA can be biodegraded by bacteria such as *Stenotrophomonas maltophilia* and *Rhodoccus opacus* and these bacteria are mesophilic with the optimum temperatures of 41 ℃ for *S. maltophilia* and 30 ℃ for *R. opacus* [18, 43]. The biodegradation of gentamicin, one of aminoglycoside antibiotics, increased by 2.4 times (p value < 0.05) with increasing temperature from 20 to 40 ℃, with the maximum removal of 47.4% at 40 ℃ [44]. The degradation of three antibiotics used in this study was generally greater at 23.0 and 31.2 °C than at 1.8 °C, and this is because of higher microbial activity at higher temperatures [8].

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Author contributions
SHK: conceptualization, methodology, formal analysis, investigation, visualization, writing—original draft, writing—review and editing; EHJ: conceptualization, methodology, formal analysis, investigation, writing—original draft, writing—review and editing, supervision, project administration, funding acquisition; GEK: methodology, formal analysis, investigation; SYP: methodology, formal analysis, investigation.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
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.

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