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Environmental fate and efficiency of bispyribac-sodium in rice soils under conventional and alternative production systems affected by fresh and aged biochar amendment

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Abstract

Irrigation and tillage practice alternatives to conventional flooding production, with or without organic amendments, are attracting great interest to adapt rice cultivation to climate change. However, they can alter the behaviour of pesticides and their efficiency against weeds. A two-year field experiment was conducted to investigate how the environmental fate and the weed control efficiency (WCE) of bispyribac-sodium (BS) were influenced by biochar produced from holm oak prunings (BHO) testing both the fresh and the aged effects. The treatments were: flooding irrigation and tillage (FT), sprinkler irrigation and tillage (ST), sprinkler irrigation and no-tillage (SNT), and the corresponding homologues with BHO addition (FT-BHO, ST-BHO, and SNT-BHO, respectively). Fresh BHO amendment decreased the sorption of BS onto the soil in all treatments, while, after aging, it also decreased sorption in FT-BHO (1.3-fold) but increased it in SNT-BHO and ST-BHO (1.1-fold). BHO addition reduced BS persistence under non-flooding and flooding incubation conditions, except for FT under the former condition for which $t_{1/2}$ increased ≈1.5-fold in both years. The addition of BHO led to a decrease in BS leaching from 58.3% and 44.6% and from 70.4% and 58.1% in ST and FT to 50.1% and 38.3% and 63.6% and 50.3% in the homologue amended soils for the fresh and aged years, respectively. While fresh BHO addition decreased the WCE of BS in SNT-BHO, ST-BHO, and FT-BHO on average by a factor of 1.5, with aged BHO there was only such a decrease (by a factor of 1.4) in FT-BHO. The use of BHO could be effective for reducing water contamination by BS in flooding or sprinkler irrigation rice farming as long as conventional tillage is used. But it may also contribute to greatly reducing the herbicide's efficiency, although with time to allow aging, this reduction would only persist under conventional flooding production.

Keywords: Herbicida efficacy; Bispyribac-sodium; Leaching; Persistence; Sorption; Sprinkler irrigation.

1. Introduction

The lack of sustainability of conventional rice (*Oryza sativa* L.) cultivation under flooding is increasingly being aggravated by a growing demand for water. The adverse impact of climate change on the hydrological cycle is also reducing water resources. This is particularly notable in Mediterranean countries where there currently can be no guarantee of the water supply for this crucial crop. This is leading to a continual fall in the area devoted to rice farming in major producing nations such as Spain (MAPA, 2019), the rice producing country ranked second of the European Union at 30% of total EU output. Therefore, in order to adapt rice cultivation to climate change, alternative irrigation and tillage practices to replace conventional flooding production are attracting great interest to ensure the crop's sustainability by enhancing water productivity, especially in water-stressed regions such as Mediterranean countries where the volume of water consumed under conventional rice production is more than reported for various nations in Asia by a factor of 2.3 (Sánchez-Llerena et al., 2016; Arunrat et al., 2020).

Growing rice aerobically using irrigation by sprinkler in Mediterranean rice agro-ecosystems under both direct seeding (no-tillage) and tillage practices has been widely perceived as a promising agricultural practice to achieve sustainability since it could help reduce water requirements, minimize greenhouse gas emissions, and decrease the levels of As in the grain (Sánchez-Llerena et al., 2016; Fangueiro et al., 2017; Spanu et al. 2021). However, the potential water-deficit stress may reduce the yield by 10-50% compared with an anaerobic system (e.g., Peng et al., 2006). Sánchez-Llerena et al. (2016) describe up to 50% reduction in rice production under aerobic conditions. Although this was only the case for soils whose levels of total organic carbon (TOC) were below 15.0 g kg^{-1}, such figures can be very common for soils used for agriculture in mediterranean environments (Muñoz et al., 2007). Therefore, in regions with limited availability of water resources and soils low in organic matter, the application of organic amendments for rice cropping under aerobic conditions could be beneficial to avoid reduced yields, ensuring the crop's sustainability with a decreasing water footprint.

Biochar is one of the principal organic amendments used worldwide due to its potential to minimize greenhouse gas emissions and enhance crop productivity. These beneficial effects have been confirmed in rice cultivation (Sun et al., 2016; Thammasom et al., 2016; Yang et al., 2019; Li et al., 2021), being the result of improvement in the soil’s biological and chemical properties (Méndez et al., 2013; Oleszczuk et al., 2014). Furthermore, biochar may have an impact on the soil's hydrological properties such as infiltration and water-holding capacity (Wong et al., 2018; Haque et al., 2021). Although biochar can be derived from a great variety of organic materials, that derived from holm oak (BHO) can be extensively produced in large areas of several Mediterranean countries (e.g. Spain, Portugal) at a reasonable price. Furthermore, due to its high TOC content, BHO is characterized by having a greater capacity to retain water and pollutants such as pesticides than biochars based on other organic materials (Takaya et al., 2016).

Although the application of biochar to agricultural soils could affect the environmental fate of pesticides and consequently their efficacy against the target weeds (Kookana et al., 2010; Gámiz et al., 2021), distinct tendencies have been widely observed depending on the characteristics of not only the amendments or soils but also of the pesticides themselves (Cabrera et al., 2011; Siedt et al., 2021). Thus, in a soil treated with 1% of hardwood biochar fomesafen sorption was 13.3 times greater, but the increase with biochar based on rice straw was 10.8-fold (Khorram et al., 2018). Cabrera et al. (2014) reported aminocyclopyrachlor sorption being on average lower by a factor of 1.8 in a macadamia nut shell biochar amended soil, while amendment with wood chip pellet biochar led to a 25-fold increase. Si et al. (2011) reported increased isoproturon sorption and persistence in various soils after charcoal amendment, with both being greatest in the soils whose cation exchange capacity and pH were lowest in value. Li et al. (2021) reported the increase in atrazine sorption after application of biochar derived from tall fescue being greatest in the soil with the lowest organic matter content. García-Jaramillo et al. (2020) found that while azimsulfuron sorption increased by a factor of 1.2 in an acidic paddy soil amended with biochar obtained from olive mill waste compost, penoxsulam sorption decreased by a factor of 1.3 in the same amended soil. Abdel Ghani et al. (2018) reported that while fenamiphos persistence increased by a factor of 6.7 in a sandy soil poor in organic matter amended with date palm and eucalyptus biochar, cadusafos persistence was unaffected in the same amended soil. Gámiz et al. (2017) found that while amendments with biochars from two hardwoods pyrolysed at 700 ºC inhibited the phytotoxicity of clomazone, there was no such effect when the herbicide used was bispyribac-sodium in the same amended soils. Furthermore, once biochar is incorporated into a soil, its physicochemical properties may by altered by weathering processes, which could modify the fate, environmental impact, and efficacy of applied pesticides (e.g. Gámiz et al., 2019).

Weed infestation is considered to be the major concern worldwide restricting rice yields, regardless of whether conventional or alternative rice production practices are applied (Sing et al., 2018; Ghosh et al., 2021). Therefore, weed management by the appropriate use of pesticides that ensures adequate efficacy is required to obtain profitable rice production, and hence help guarantee the crop's sustainability. In this sense, acetolactate synthase (ALS) inhibiting herbicides such as bispyribac-sodium (BS) (sodium 2,6-bis[(4,6-dimethoxypyrimidin-2-yl)oxy]benzoate) is recognized as being one of the most effective post-emergence herbicides (Mascanzoni et al., 2018). It is extensively used in rice cropping for control of a wide range of weeds (sedges, grasses, and broadleaf weeds). However, BS may negatively impact not only non-target soil microorganisms (Kumar et al., 2020) but also aquatic organisms including macroinvertebrates (Stenert et al., 2018) and freshwater fish

(Pradhan et al., 2020). Furthermore, the high water solubility of this compound (64 g L^{-1}) and its moderate-to-high persistence in soils increase its potential risk for water resource contamination. For instance, Vieira et al. (2016) detected high levels (3.5 μg L^{-1}) of BS in water samples of regions associated with irrigated rice production.

Despite the increasingly common use of biochars as organic amendment to enhance the agronomic and environmental sustainability of rice cultivation (Asadi et al., 2021), and that BS has a great potential risk for contaminating water resources, to the best of our knowledge, only three works (Gámiz et al., 2017; Sharma et al., 2020; Kaur et al., 2022) have as yet been conducted to assess how such amendments can affect the herbicide's behaviour. In these studies, the biochars were applied under laboratory conditions, and no aging effects were evaluated. In particular, we found no published research focused on how BS's fate and its effectiveness in controlling weeds may be affected by biochar amendment when, in field experiments, it is added to soils under different management regimes of irrigation and tillage. Therefore, the objective of the present work was to assess, in a two-year field experiment, how the sorption-desorption, leaching, dissipation, and efficacy of BS was influenced by fresh BHO applied to rice soils under conventional and alternative production systems. Since weathering and aging processes could greatly modify the original BHO properties, which in turn could influence BS's environmental fate and availability to weeds, the effects of BHO aging under natural field conditions were also examined.

2. Material and Methods

2.1. The herbicide

BS analytical standard (98.3% purity) was procured from Dr Ehrenstorfer, GmbH (Germany). Its properties are described in BPDB (2019). BS assays were performed by high-performance liquid chromatography (HPLC) using a Waters 600E chromatograph coupled to a Waters 996 diode-array detector. The conditions used are presented in detail in Text S1 of the Supplementary Material (SM).

2.2. The biochar

The commercial amendment (BHO) employed in the field experiment was purchased from Carylevere Co., Ltd (Zahinos, Spain). It was produced from prunings of holm oak by pyrolysis at 550°C (48 h). Prior to assay and application, the BHO underwent milling to a 2-mm sieving size. BHO properties of carbon (TC), hydrogen (TH), nitrogen (TN), ash, oxygen, water-soluble organic carbon (WSOC) contents, and specific surface area (SSA), Fourier-transform infrared (FTIR) spectra, porosity, pH, and electrical conductivity were measured as detailed previously by López-Piñeiro et al. (2022) and presented briefly in Text S2 of SM. The properties of aged BHO were determined after harvest in the second year of the experiment. For this, BHO particles were separated from samples of soil down to 20-cm depth corresponding to the FT-BHO, ST-BHO, and SNT-BHO treatments. Suspensions of these BHO samples were prepared in distilled water at a 1:10 w/v dosage, and then shaken to eliminate any particles of soil. In accordance with Koide et al. (2011), the BHO was rinsed four times using distilled water before assay. Table 1, which is adapted from López-Piñeiro et al. (2022) presents a selection of the aged and fresh BHO characteristics. Additionally, the FTIR characterization is presented in Fig. S1 (SM) and briefly discussed in Text S3 of SM.

2.3. Design of the experiments, sampling, and assay

A two-year (2018-2019) field trial was conducted in a rice paddy located in the province of Badajoz (38°55'N; 6°57'W; SW Spain), with climate classified as Mediterranean semi-arid (mean yearly temperature 16.2 °C and rainfall 460 mm). This experimental area had been managed for 14 years as conventional rice (*O. sativa* L.) cropping by flooding irrigation and tillage. The soil (0-20 cm) is loam textured (clay 20.8%, silt 28.9%, and sand 50.3%). The experimental design involved a total of 18 plots (six treatments with three replicates), with each plot measuring 10 m × 18 m (180 m^2). The applied treatments were: conventional flooding irrigation and tillage (FT), sprinkler irrigation and tillage (ST), sprinkler irrigation and no-tillage (SNT), and the corresponding homologues with only first-year BHO addition (FT-BHO, ST-BHO, and SNT-BHO treatments, respectively). The BHO application rate (28 Mg ha^{-1}) was applied by spreading onto the surface of the soil of the FT-BHO, ST-BHO, and SNT-BHO treatments in April 2018, and then it was incorporated into the soil by a rotary hoe. After rice harvest (September 2018 and 2019), four subsamples of topsoil (0-20 cm) were collected for each of the plots to make a composite sample which was used to determine BS sorption-desorption, leaching, and dissipation. The data obtained in the year one and year two following BHO administration were used for evaluating its effects both "fresh" as well as "aged", respectively. Selected soil properties (WSOC, TC, and TN contents, EC, and pH) of the unamended and BHO-amended soils are presented in Table S1 of the SM. Please refer to López-Piñeiro et al. (2022) for more details.

2.4. Experiments of adsorption and desorption

Isotherms of BS adsorption-desorption for the soil samples of unamended and BHO-amended treatments were determined in triplicate in accordance with López-Piñeiro et al. (2016) using the batch equilibration method. Briefly, soil samples (5 g) were treated by mechanical shaking at 20±1°C for 24 h with 10 mL of solutions of BS in 0.01M $CaCl_2$ at initial concentrations (C_i) of 0.5, 2.5, 5, 10, and 20 µM, which cover the field application rates frequently used by farmers in the region of the study (0.1-0.5 kg ha^{-1}). BS adsorption-desorption data were fitted to the Freundlich equation ($C_s = K_f C_e^{nf}$). Detailed information on these experiments is presented in SM (Text S4).

2.5. Studies of the dissipation of the herbicide

For the dissipation of BS, soil samples from treatments with and without BHO addition were analysed under two incubation conditions (flooded and non-flooded). BS was spiked to give an application rate of 1.63 μg g^{-1}. For each treatment, triplicate soil samples were removed at selected intervals after BS application (up to maximum of 49 days) for its residual extraction. The BS was extracted with 10 mL of a 60:40 (v/v) distilled water/methanol mixture, and an HPLC analysis was made of its supernatant residues. Measurements for the original and BHO-amended soils were fitted to a first-order kinetics equation in order to calculate the respective half-lives ($t_{1/2}$). The activity of dehydrogenase (DHA) for the two conditions of incubation was also determined employing INT as substrate in accordance with García et al. (1993). Additional details of these studies are given in Text S5 of SM.

2.6. Studies of the leaching

To determine the leaching of BS, triplicates of air-dried soils from non-amended as well as BHO-amended treatments were introduced by packing into 5-cm inner diameter × 30-cm length PVC columns. They were then oversaturated using 0.01 M $CaCl_2$, allowing 24 h for the excess to drain. BS was then added at a rate of 0.5 kg a.i./ha onto the top of the soil columns. Each column was eluted each day by adding 50 mL 0.01M calcium chloride solution, with each leachate being assayed using high-performance liquid chromatography. Terminated the period of monitoring, all columns were sectioned into each of the 5-cm depths to determine the BS remaining. BS extraction was as for the studies of dissipation described above. Further details of these leaching experiments are provided in SM (Text S6).

2.7. Bioassays

For the aged and fresh years, a laboratory bioassay was conducted to assess how the phytotoxicity of BS is influenced by the addition of BHO to soils that had been subjected to distinct tillage and irrigation managements. Triplicates of air-dried soils (50 g) were put into pots of 30 cm^2. The soils under non-flooding irrigation (SNT, ST, SNT-BHO and ST-BHO) were incubated at 80% field capacity, and those under flooding irrigation (FT and FT-BHO) at 1:1.25 w/v soil-to-water ratio. For incubation, the pots were randomly placed inside a growth chamber and kept under conditions of 25 °C and 12-h daylight for 14 days. Then, for each treatment, the weeds were removed by hand, and 10 pre-germinated seeds of *Echinochloa crus-galli* L. (one of the main weeds causing critical rice yield losses) were put onto the soil surface of each pot. After 10 days, BS was applied to one set of pots at the recommended dosage of 100 g ha^{-1}, leaving as controls another set without herbicide. In order to simulate field BS application for treatments under flooding irrigation, the excess of water was carefully removed from the corresponding pots until two days after its application. After 14 days of BS application, the weights of *E. crus-galli* L. were measured to determine the weed control efficacy (WCE) in all treatments, which was calculated as WCE = (DWC - DWT) / DWC, where DWC and DWT are the dry weights of weeds in the control and in the BS treated pots, respectively (Mohammed et al., 2016).

2.8. Statistical analyses

Statistical analyses (Pearson's correlation, ANOVA, Duncan's test) were done with the use of IBM's SPSS (vn. 22) software package. A *p*-value >0.05 was considered to indicate statistical non-significance.

3. Results and Discussion

3.1. Sorption-desorption studies

Figure S2 shows sorption–desorption isotherms of BS for fresh and aged years. For both years, all sorption isotherms from original and BHO amended soils were appropriately described by the Freundlich model (R^2=0.972-0.998; Table 2). These results agree with Kaur et al. (2022) who indicated that the Freundlich model was the most satisfactory to describe the adsorption behaviour of BS in unamended and rice-straw biochar amended soils. Moreover, the values of nf (<1) indicate that BS sorption was greatly dependent on its initial concentration in the solution. However, C-shaped BS adsorption isotherms (nf ≈1) were reported by Kaur et al. (2022) for a sandy loam soil with and without addition of rice straw biochar, which may be attributable to the different properties of the soils and biochar used. The treatments significantly (p<0.001) affected the BS sorption, with differences between the effects in the fresh and aged years as shown by the significant treatment × year interaction (p<0.001; Table 2). For the soils without BHO amendment, the BS K_f values varied from 0.494 to 1.09 and from 0.583 to 0.929 in the first and second year, respectively (Table 2), which are of the same order of magnitude as those found by Singh and Singh (2015) who reported values ranging from 0.37 to 0.87 for Indian soils with lower TOC content (3.0-6.3 g kg^{-1}) and values of pH of 5.2-7.9. Our K_f values are lower than those reported by Gómez et al. (2019) who found values ranging from 0.634 to 1.531, also in rice soils from Spain although with lower pH values (4.9-6.1) and slightly higher TOC contents (10.2-15.1 g kg^{-1}). However, Gámiz et al. (2017) found, in an agricultural soil also from Spain with TOC of 13 g kg^{-1} but pH of 7.9, a lower value of K_f (0.2) than in our study. Furthermore, the BS sorption in our study was much lower than that found by Chirukuri and Atmakuru (2015) who reported K_f values of 3.4 and 5.6 for soils from the United States and 3.9 and 4.8 for soils from the Netherlands (with 39 and 33, and 34 and 44 g kg^{-1} TOC, and pH values of 6.5 and 6.3, and 5.4 and 5.2, respectively). This indicates that there should be expected a much greater potential for water resource contamination by BS (and consequently less safety in its use) when this compound is applied to Mediterranean fields with edaphic characteristics such as those in this study in comparison with other soils which have characteristics of more acidic pH values and/or very high values of TOC content.

For both years, the BS sorption was significantly greater in FT than in SNT and ST treatments (p<0.05). The greatest differences were found in the first year. Thus, whereas in the first year the FT K_f values were 1.9 and 2.2 times as great as in ST and SNT, respectively, in the second year they were greater than in ST and SNT by a factor of 1.6 (see Table 2). This is in agreement with López-Piñeiro et al. (2016) who, also for rice soils from Spain, concluded that in the short-to-medium term an increase in the values of soil pH resulting from the flooding to non-flooding irrigation transition under no-tillage and tillage management resulted in reduced BS sorption by 2.4 times. Indeed, when only our original soils were included in a correlation analysis, K_f showed a significant negative correlation with respect to pH (r = -0.958, $p < 0.01$). In accordance with Hyun et al. (2003) and Kaur et al. (2022) our results appear to corroborate that the observed pH values in SNT and ST management (pH>6.3) can lead to decreasing the proportion of neutral BS molecules which could be readily adsorbed onto the negatively charged surface of soil colloids. In addition, the presence of greater WSOC in SNT and ST than in FT treatments may also have resulted in lower BS sorption due to the competition between WSOC and BS molecules for occupying available sorption sites (Cabrera et al., 2014). The BHO application influenced BS sorption significantly (p<0.05) in flooded and non-flooded treatments for both years. However, compared with the respective original soils, in the fresh case, BHO application decreased the BS K_f values in SNT-BHO, ST-BHO, and FT-BHO 1.1-, 1.2-, and 1.6-fold. In the aged case, these values also decreased in FT-BHO by a factor of 1.3 but slightly increased in SNT-BHO and ST-BHO (by a factor of 1.1; Table 2), indicative of BHO amendment's impact on BS sorption in soils managed under different irrigation and tillage practices also being time dependent. In part, an explanation for these findings may lie in the increases observed in the pH values of the BHO-amended with respect to the corresponding original soils. Indeed, K_f was significantly (negatively) correlated with soil pH (r =-0.831; p<0.01), confirming the key role it plays in BS sorption as previously reported by Chirukuri and Atmakaruru (2015) for instance. Thus, according to different authors (Kah and Brown, 2006; Gómez et al., 2019), increasing pH after addition of organic amendments such as BHO could lead to an increase in the ratio of the BS anion form which may be less easily adsorbed than the protonated fraction. However, the slight increase in the BS K_f values observed in non-flooded BHO-amended soils (SNT-BHO and ST-BHO) compared with the corresponding original soils (SNT and ST) in the aged year cannot be attributed to their different pH since both pH and K_f had the greatest values in BHO-amended soils (Table S1 and Table 2). This could well be ascribed to the additional sorption sites promoted by the significantly (p<0.05) greater SSA (Table1) observed in aged than in fresh BHO (Martin et al., 2012; Gámiz et al., 2019). Greater increases (by factors of 2.5 and 1.9) in BS sorption were found by Gámiz et al. (2017) when two biochars produced from hardwood at a pyrolysis temperature similar (500°C) to the BHO applied for this study were used as amendment, although this was a laboratory experiment in which the initial soil, with a very low K_f value (0.2), was amended with a dose of biochars approximately twice that of the present study, and aging effects were not measured. Similar findings were observed by Kaur et al. (2022) who found a significant positive correlation between BS sorption capacity and SSA, although in a study in which only a fresh biochar effect was measured.

Similar to sorption, BS desorption was significantly (p<0.001) affected by which treatment was applied, as well as the effects in the two years (fresh and aged) being different as shown in the significance of the treatment × year interaction (Table 2; p<0.001). In the case of soils without BHO amendment, D values were lower in ST and SNT than in FT by factors of 2.0 and 1.3 and 1.4 and 1.7 for the first and second years of the experiment, respectively (Table 2). After BHO field addition, the values of D were significantly (p<0.05) reduced in flooded and non-flooded treatments in both years, although this effect was more evident in the former. A decrease in desorption after rice straw biochar addition was also found for fomesafen (Khorram et al., 2018) and imazapyr and imazapic (Yavari et al., 2016), suggesting that the bond between BS and unamended soils is less robust than between BS and biochar particles (Ogura et al., 2021). Moreover, similarly to the original soils, BS desorption was significantly greater in TF-BHO than in NTS-BHO and TS-BHO for the fresh (by factors of 2.3 and 1.7) and aged (by factors of 1.5 and 1.4) years (Table 2), confirming that in unamended and BHO-amended soils the sorbed BS may be more weakly retained in those under flooding than under non-flooding, irrespective of the tillage practices implemented. The order of BS desorption may be explained by the soil organic matter (TOC and WSOC) (Tables S1 and Table 2). Indeed, D was significantly and negatively correlated with TOC (r=-0.497; p<0.05) and WSOC (r=-0.333; p<0.05). These results agree with previous reports of lower reversibility of BS (Gómez et al., 2019) and another anionic herbicide (MCPA) (López-Piñeiro et al., 2014) with increasing TOC and WSOC in rice and olive grove soils, respectively, both amended with olive mill waste. However, greater reversibility of terbuthylazine and diuron (Cabrera et al., 2007) and metribuzine (López-Piñeiro et al., 2013) was also found in olive mill waste amended soils than in unamended soils, which was attributed to the greater WSOC in the former, coherent with the desorption capacity of pesticides applied to soils being influenced not just by the most reactive and mobile source of soil carbon but also by the pesticides' diversity of chemical structures. Compared with the fresh year, a marked increase in sorption reversibility was observed in the soils after BHO aging (Table 2), which could be due to the significant differences (p<0.05) found between the micropore volume to total pore volume ratios of the fresh and aged BHO (Table S2) (Khorram et al., 2018). Also, this increase in BS desorption because of the aging effect may be attributable to blockage in adsorption sites by minerals, acids, and oxides in soils (Ogura et al., 2021), which would have been more significant under flooding conditions. Our results suggest that, besides a decline in the risk of water resource contamination as a consequence of the increased sorption capacity in non-flooded BHO treatments, a better bioavailability and weed control effectiveness of BS could also be expected in both non-flooded and flooded BHO treatments with aging time.

3.2. Dissipation studies

The BS dissipation curves and DHA for unamended and BHO-amended soils are shown in Fig. 1. For the fresh and aged years, the data fit first-order kinetics for non-flooded (R^2>0.870) and flooded (R^2>0.855) conditions (Table 3). In each of the two years, the DHA values measured for the whole incubation period (DHAT) were lower under non-flooded than under flooded conditions of incubation, especially in the soils under flooding irrigation, with DHAT values in these treatments being up to factors of 3.0 (year fresh) and 3.1 (year aged) lower under non-flooded conditions of incubation (see Table 3). Gómez et al. (2019) also found lower values of DHAT under non-flooded than flooded conditions of incubation, although using olive mill waste as amendment of organic type in rice-cropping soils following the application of BS. BHO application with statistical significance (p<0.05) increased DHAT values in all treatments and under both incubation conditions, an effect which is attributable to the greater organic matter content of the BHO-amended soils. Indeed, significant positive correlations were found between DHAT and TOC under flooding (r=0.403, p<0.05) and non-flooding (r=0.541, p<0.01) incubation conditions. These results are consistent with a previous meta-analysis by Liao et al (2022) who observed DHA increases when biochar produced at low temperature is applied, suggesting that TOC is one of the dominant factors influencing biochar effects on soil enzyme activities.

The BS dissipation was significantly (p<0.001) treatment affected. The differences before with respect to after BHO aging are shown by the significance (p<0.001) of the interaction treatment × year (Table 3). As was to be expected according to the K_f values, overall a significant increase in the BS persistence was observed for the unamended and BHO-amended treatments of the aged compared with the corresponding fresh-year soils, with $t_{1/2}$ values up to 1.5 times greater for treatments without BHO amendment in both experimental incubation conditions and up to 1.4 and 1.3 times greater for treatments with BHO amendment under non-flooded and flooded conditions of incubation, respectively (Tables 2 and 3).

For soils without BHO amendment, the $t_{1/2}$ values varied from 31.9 to 86.4 d and from 34.4 to 129 d under non-flooded and flooded conditions of incubation, respectively (Table 3). These are of the same order as those found by López-Piñeiro et al. (2016) under flooded (45.4 to 131.8 d) but slightly greater than those under non-flooded (31.0 to 51.5 d) experimental conditions. However, the values of the present work are much greater than those reported by Gámiz et al. (2017) of 21 d for a non-flooded type of condition, although this was for a soil of much lower capacity for sorption (K_f=0.21) which might have the result of greater biodegradation availability of the compound, and with the samples being moistened to 30% of field capacity. Except for the FT treatment, the BS persistence for soils without BHO amendment was significantly (p<0.05) lower in the soils under non-flooded than under flooded experimental conditions in the two years of the study, with $t_{1/2}$ values increasing up to 1.4- and 1.9-fold for year one and the year two of the study, respectively (see Table 3). Kalsi and Kur (2019) and Sharma et al. (2020) also found lesser persistence of BS under non-flooded than under flooded conditions of incubation as a consequence of a poorer ability of the anaerobic microbial community to dissipate BS, showing soil moisture to be a major factor influencing herbicide persistence because of its being essential for microbial activity. Furthermore, despite BS sorption being significantly greater in the treatment under flooding (FT) than in those under sprinkler irrigation (SNT and ST), the BS dissipation rate was significantly (p<0.05) greater in FT than in SNT and ST in both years of the study, with $t_{1/2}$ values increasing up to 1.9-fold in SNT and ST under non-flooded, and up to 2.3- and 2.7-fold in SNT and ST, respectively, under flooded incubation conditions (Table 3). When only original soils were included in a correlation analysis, $t_{1/2}$ showed a significant positive correlation with pH for non-flooded (r=0.736, p<0.01) and flooded (r=0.685, p<0.01) incubation conditions, indicating that BS dissipation rates decreased in response to increased pH of the soil that resulted from the conventional flooding to alternative sprinkler irrigation regime transition irrespective of whether or not tillage was applied. This is consistent with

Chirukuri and Atmakuru (2015) and Kalsi and Kaur (2019) who reported that BS was less stable and more available for dissipation with decreasing soil pH due to diminished hydrolysis of this compound at the higher pH values. In addition, Chirukuri and Atmakuru (2015) found that TOC had a positive influence on BS dissipation rates, although their study used 21 unamended soils from different locations with a wider range of TOC values (3.5-44 g kg^{-1}) than in our work (9.3-10.7 g kg^{-1}).

As was observed for the original soils, the BS persistence for soils with BHO amendment was also significantly (p<0.05) lower in the non-flooded than the flooded experimental conditions soils in the two years (fresh and aged), although only for the treatments under non-flooding irrigation (SNT-BHO and ST-BHO). Thus while for these treatments the $t_{1/2}$ values increased by factors of 1.7 and 1.8 for the treatment under flooding irrigation (FT-BHO) they decreased by factors of 1.6 and 1.8 for the fresh and residual years, respectively (Table 3). This decrease may be explained by the DHAT values which resulted to be factors of 3.0 (fresh) and 2.8 (aged) greater in FT-BHO under flooded than under non-flooded conditions, respectively (Table 3). Indeed, $t_{1/2}$ was negatively correlated significantly with DHAT for non-flooded (r=-0.539, p<0.01) and flooded (r=-0.620, p<0.01) experimental incubation conditions. The field BHO application significantly (p<0.05) decreased BS persistence in all treatments and under both incubation conditions, except for FT-BHO under non-flooded conditions in which, relative to FT, the $t_{1/2}$ values increased from 31.9 to 48.4 d and from 49.4 to 66.3 d for the fresh and aged years, respectively (Table 3). This increase may be explained by the expected lesser availability of BS for dissipation with increasing soil pH from 5.5 to 6.4 (fresh year) and from 5.6 to 6.5 (aged year) (Table S1), coupled with the poorer ability of soil microbial communities to degrade this compound due to their lack of adaptation to aerobic conditions after 14 years under flooding irrigation management (Sharma et al. 2020). The observed decrease in BS persistence after BHO amendment was more evident in the aged year, in which the $t_{1/2}$ values were 1.2, 1.6, and 1.3 times lower in SNT-BHO, ST-BHO, and FT-BHO, as well as lower by factors of 1.3 and 1.8 in ST-BHO and SNT-BHO than in corresponding unamended soils, for flooded conditions of incubation and non-flooded conditions, respectively (see Table 3). In accordance with Khorram et al. (2016), the observed enhancement in BS dissipation after BHO application may be attributed to microbial stimulation as a result of the high organic matter content present in this amendment. Indeed, $t_{1/2}$ was significantly negatively correlated with TOC for non-flooded (r=-0.471, p<0.01) and flooded (r=-0.420, p<0.01) incubation conditions. Significant decrease in BS persistence after rice straw biochar application has been reported by Sharma et al. (2020) under flooded and non-flooded conditions, although unlike our work this was in a laboratory study with soils not under different management regimes of tillage and irrigation and without measuring any aging effect. However, Gámiz et al. (2017) found longer persistence of BS in a soil that had been amended using two types of biochars produced from hardwood, although that study was conducted only under a non-flooded condition in which the biochars were pyrolysed at a higher temperature (700°C) than the BHO in our study (550°C), which could mean opposite effects on soil enzymes activities (Liao et al., 2022), thereby affecting the herbicides dissipation. Likewise, other studies found increases in persistence of different pesticides (e.g. MCPA, carbofuran and dimethyl disulphide) in soils amended with different biochars (Khorram et al., 2016; Han et al., 2017). Besides differences in the soils' physicochemical properties due to the different management regimes, these contradictory results also highlight how important are the particular characteristics of the pesticides and biochar when their behaviour is analysed in amended soils (Sharma et al. 2020).

3.3. Leaching studies

Figure 2 shows the BS breakthrough curves. Table 4 lists the proportions of BS first leached and then extracted from the columns of soil once terminated the leaching study. Total BS leaching was affected significantly (p<0.001) by the treatment, and there were differences between the two years (fresh and aged) as shown in the significance (p<0.05) of the interaction treatment × year (see Table 4). In soils without BHO amendment, the amount of BS leached ranged from 44.6% to 58.3% (year 2018) and from 58.1% to 70.4% (year 2019) of the total of the compound initially applied (Table 4), which are somewhat greater values than those reported (40.2-55.3%) by Gómez et al. (2019) also in rice soils. Greater percentages of leached BS (76.3-87.1%) were found, however, by Kaur et al. (2021), although in alkaline soils (pH=8.0-8.8) with very little organic matter content (TOC=1.4-3.6 g kg^{-1}). The total of BS leached was greater in SNT and ST than in FT by factors of 1.3 and 1.3 and 1.1 and 1.2, for the first and the second year of the experiment, respectively, suggesting that the soil property changes following the implementation of alternative rice production under non-flooding irrigation could enhance the leaching of BS, especially under tillage management. These results are consistent with those reported by Gómez et al. (2019) who, also for rice soils from Spain, reported a greater amount of BS leached in SNT and ST than in FT management, which was attributed to the lower BS sorption capacity and much greater persistence observed in the treatments under non-flooding irrigation. Thus, in the present study (fresh year), the values of K_f in FT were 2.2 and 1.9 times greater (Table 2), and the values of $t_{1/2}$ 2.2 and 2.5 times lower (Table 3) than in SNT and ST, respectively.

Despite the significant decrease in BS sorption capability observed in all treatments with BHO amendment in the fresh year and in the FT-BHO treatment in the aged year (Table 2), except for the SNT treatment, the field BHO amendment was followed by a decline in BS leaching from 58.3% and 44.6% and from 70.4% and 58.1% in ST and FT, to 50.1% and 38.3% and 63.6% and 50.3% in the homologue amended soils for the fresh and aged years, respectively (Table 4; Fig. 2). This may be attributable to the lesser persistence observed in the ST-BHO and FT-BHO relative to the homologue non-amended treatments (see Table 3 and Table 4). In fact, the proportion of BS leached was positively correlated with $t_{1/2}$ values under non-flooding (r= 0.475, p<0.01) and flooding (r=0.827, p<0.01) incubation conditions.

These results agree with Gómez et al. (2019) who, also for rice soils, attributed the significant decrease observed in BS leaching of amended compared with unamended soils to a lower persistence, although that study used olive mill waste instead of BHO as organic amendment. However, despite the significant decrease in BS persistence also observed in SNT-BHO compared with SNT, no significant differences (p>0.05) between these cases were observed for the amount corresponding to BS leached in the two years (fresh and aged; see Table 4). An explanation may be the greater content of WSOC found for the treatments under no-tillage which could act as co-transporter for BS (Peña et al., 2015), and this could have counterbalanced the favourable effect of the decreased persistence on the reduction of BS leaching. Indeed, a significant positive correlation (r=0.444, p<0.01) was found between the percentage of BS leached and WSOC. Therefore, although the transition from a flooding to a non-flooding irrigation regime could enhance the risk of water contamination by BS, our results suggest the fresh or aged BHO may reduce this effect in both irrigation systems, particularly under tillage practices. Similar findings were observed by Kaur et al. (2022), who indicated that the application of rice-straw biochars might be an effective management practice in controlling the leaching potential of BS. In addition, for a range of different herbicides, biochar has been shown to have a great potential to reduce the leaching capacity of these compounds (e.g., Trigo et al. 2016; Mendes et al. 2018). However, López-Piñeiro et al. (2022) reported that, after BHO aging, the capacity of this amendment to mitigate clomazone leaching decreased, especially under flooding management and conventional tillage, highlighting how the behaviour of applied pesticides in soils with BHO amendment strongly depends on properties specific to the compound selected.

At termination of the trial concerning leaching, no significant differences (p>0.05) were found between managements or years in the total amount of BS remaining in the soil columns (Table 4). Nonetheless, except for the treatment with flooding irrigation, the amounts of BS recovered were on average 1.9 and 1.6 times lower in the treatments with BHO amendment

(SNT-BHO and ST-BHO) than the homologue unamended soils for the fresh and aged years, respectively. This is coherent with the results of the dissipation study, with the smaller amount of BS recovered in BHO-amended soils being attributable to its lower persistence. Indeed, there was a significant positive correlation of the BS recovered with the $t_{1/2}$ values (r=0.704, p<0.01).

3.4. Weed control efficacy

The weed control efficacy (WCE) of BS for unamended and BHO-amended soils is shown in Fig. 3. The WCE was significantly (p<0.001) affected by treatment, there being differences between the two years of BHO aging. This is shown in the significance (p<0.001) of the interaction treatment × year (see Table S3). In soils without BHO amendment, and for both years, the efficacy of BS against *E. crus-galli* L. was greater in the treatments under non-flooding than under flooding types of irrigation, regardless of which tillage system had been used, although this effect was only significant (p<0.05) in the first year of the study with WCE values decreasing from 80.4% (SNT) and 83.8% (ST) to 56.4% (FT) (Fig. 3). When only original soils were included in the correlation analysis, WCE showed a significant negative correlation with K_f values (r=-0.925, p<0.01), indicating that a decrease in the sorption capacity of BS resulting from the transition from flooding to sprinkler irrigation, as was discussed above in the sorption-desorption section, could enhance the weed control effectiveness of this compound.

The BHO application significantly (p<0.05) influenced the WCE of BS in flooded and non-flooded treatments for both years. However, compared with the corresponding original soils, in the fresh year the application of BHO decreased WCE BS values in SNT-BHO, ST-BHO, and FT-BHO 1.6-, 1.2-, and 1.7-fold, in the aged case these values also decreased in FT-BHO by a factor of 1.4 but increased, although without significance (p>0.05), in SNT-BHO and ST-BHO (by factors of 1.2 and 1.1, respectively; Fig. 3), indicating that the impact of BHO amendment on the effectiveness of BS in soils managed under distinct tillage and irrigation practices was time dependent due to the aging process. These results may in part be attributed to the significantly ($p<0.05$) lower percentage of BS desorption observed in all BHO-amended soils compared with unamended soils, especially in the fresh year (Table 2), which could have lessened its availability to control *E. crus-galli* L. Therefore, as suggested by Mendes et al. (2019), it is extremely relevant to gain a better understanding of how biochar application affects herbicide sorption–desorption to determine these chemicals' weed control efficacy. Moreover, the findings might also have their explanation in the observed lower BS persistence for the BHO-amended soils compared with their corresponding original soils (Table 3). Indeed, WCE was significantly positively correlated with $t_{1/2}$ values ($r=0.625$, $p<0.01$). These results agree with Kalsi and Kaur (2019) who indicated that dissipation is one of the fundamental processes which determine the effect of herbicides on the environment as well as their weed control efficacy. However, the increases in the effectiveness of BS observed in non-flooded BHO-amended soils (SNT-BHO and ST-BHO) compared with the corresponding original soils (SNT and ST) in the aged year cannot be attributed to differences in their persistence, since the greatest values in WCE (Fig. 3) and lowest in $t_{1/2}$ (Table 3) corresponded to those BHO-amended soils. This could well be ascribed to the observed much lesser desorption of BS in the fresh than in the aged amended soils, given that D increases from 5.92% and 7.97% to 21.1% and 22.3% for SNT-BHO and ST-BHO, respectively (Table 2), which may lead to an increase in the herbicide's bioavailability. Our results contrast with those of Gámiz et al. (2017) who found no differences in BS efficacy against *Eruca vesicaria* plants in unamended and amended soils with two different biochars, although that study was conducted only under non-flooding conditions in which the aging effect was not measured, and using compounds pyrolysed at a higher temperature (700°C) with SSA values, on average, 15 times greater than the BHO amendment used in the present work.

4. Conclusions

The use of BHO as amendment in conventional and alternative rice production systems modified the environmental fate and efficacy of BS against weeds in a form that was dependent on the irrigation and tillage regimes implemented as well as on BHO that has aged. Consequent from the soil property (pH, TOC, WSOC) and BHO (SSA, pore-size distribution) changes, BS sorption together with its reversibility decreased for all the BHO-amended soils although, after the amendment's aging, while this effect on reversibility was maintained, that corresponding to sorption was present only in soils managed under conventional flooding management. As a consequence of microbial stimulation resulting from the high organic matter content present in the BHO, both the fresh and the aged amendments decreased BS persistence in the soil, whether under flooding or sprinkler irrigation. Despite the transition to sprinkler irrigation leading to more BS being leached, the lower persistence of this herbicide in fresh and aged BHO-amended soils reduced BS leaching, although only in soils under conventional tillage irrespective of the irrigation regime implemented. Further research, including the formation of possible metabolites in dissipation and leaching studies, is required for a better understanding of how the environmental fate of BS is influenced by alternative production systems using BHO amendment. Additionally, BS's weed control efficiency was enhanced as a consequence of the transition from flooding to sprinkler irrigation, reflecting the decrease in its sorption capacity and greater persistence. Also as a consequence of the changes in the sorption-desorption and dissipation processes, BHO reduced BS's efficiency in all the amended soils, although after aging this effect only persisted in soils subjected to conventional flooding irrigation. Therefore, although alternative rice production systems using sprinkler irrigation might increase the risk of water contamination by BS, amendment with BHO can be an effective strategy to mitigate this risk under both flooding and sprinkler irrigation but only with conventional tillage. However, BHO amendment might also greatly reduce BS's weed control efficiency in soils under regardless of whether the system is sprinkler irrigation or flooding, although after a time of aging this effect would only persist for conventional flooding rice production.

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Table 1

Selected properties of the fresh and aged biochar.

	Fresh	Aged SNT-BHO	Aged ST-BHO	Aged FT-BHO
TC (%)	77.1c	74.1a	74.0a	75.2b
TH (%)	3.61c	3.22b	3.22b	3.18a
TN (%)	0.470a	0.690c	0.690c	0.520b
TO* (%)	18.8a	22.0c	22.1c	21.1b
Ash (%)	9.94a	10.9a	13.8b	15.7c
H/C (molar ratio)	0.562c	0.521b	0.522b	0.507a
O/C (molar ratio)	0.183a	0.223c	0.224c	0.210b
pH	9.08d	6.78c	6.21a	6.38b
EC (dS m^{-1})	3.54d	0.603c	0.373a	0.457b
WSOC (mg kg^{-1})	368c	273b	261ab	258a
SSA (m^2 g^{-1})	17.4a	20.0b	52.7c	67.1d

The data for total carbon (TC), total hydrogen (TH), total nitrogen (TN), total oxygen (TO), electrical conductivity (EC), water-soluble organic carbon (WSOC), and specific surface are (SSA) are mean values. *TO calculated assuming < 1% of S without ash content. Values with the same letter within a row are not significantly different at the $p< 0.05$ level of probability

Table 2
Effect of different management regimes on bispyribac-sodium sorption–desorption parameters.

		n_f	K_f	R^2 sor	% D†	R^2 des
2018						
SNT		0.848aA	0.494aA	0.982	30.6cA	0.988
SNT-BHO		0.910abA	0.456aA	0.972	5.92aA	0.949
ST		0.909abA	0.562bA	0.984	20.9bA	0.999
ST-BHO		0.917abA	0.453aA	0.995	7.97aA	0.991
FT		0.929bA	1.09dB	0.991	41.1dA	0.990
FT-BHO		0.916abA	0.672cA	0.983	13.6abA	0.904
2019						
SNT		0.865abA	0.598aB	0.996	25.8bA	0.915
SNT-BHO		0.832aA	0.649bB	0.998	21.1aB	0.974
ST		0.892bcA	0.583aB	0.997	30.5cA	0.786
ST-BHO		0.869abA	0.652bB	0.995	22.3aB	0.885
FT		0.889bcA	0.929dA	0.997	43.5dA	0.996
FT-BHO		0.933cA	0.708cA	0.998	31.4cB	0.966
Y	F-values	2.69NS	80.4***	-	59.4***	-
M	F-values	9.16*	356***	-	54.8***	-
Y x M	F-values	3.44*	46.7***	-	14.1***	-

ANOVA factors are: Y, year; M, management regime; Y × M, interaction year × management regime; F-values indicate the significance levels *$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$, respectively, and NS: not significant. Different letters indicate significant differences ($p < 0.05$) between management regimes in the same year (lower case letters) and between years within the same management regime (upper case letters).
†The percentage of D was calculated after three cycles of desorption.

Table 3

Effect of different management regimes on dehydrogenase activity and bispyribac-sodium dissipation parameters.

	$t_{1/2\ 80\%}$ (days)	$R^2_{80\%}$	$t_{1/2\ 1:1.25}$ (days)	$R^2_{1:1.25}$	$DHAT_{80\%}$ (µg INTF g^{-1} h^{-1})	$DHAT_{1:1.25}$ (µg INTF g^{-1} h^{-1})
2018						
SNT	60.6dA	0.871	75.0cA	0.950	6.35bA	6.61bA
SNT-BHO	38.1bA	0.940	63.8bA	0.931	7.35cA	9.91cA
ST	59.5dA	0.934	86.6dA	0.855	4.49aA	5.00aA
ST-BHO	49.8cA	0.935	76.9cA	0.769	6.12bA	6.59bA
FT	31.9aA	0.961	34.4aA	0.955	6.05bA	10.5cA
FT-BHO	48.4cA	0.944	31.3aA	0.899	10.1dA	30.2dA
2019						
SNT	86.4cB	0.954	105dB	0.945	7.62bA	10.6bA
SNT-BHO	48.6aB	0.992	85.9cB	0.931	12.3dB	16.8cB
ST	67.7bB	0.992	129eB	0.955	4.96aB	7.50aB
ST-BHO	50.4aA	0.982	79.9cA	0.897	7.49bA	10.8bB
FT	49.4aB	0.979	46.6bB	0.914	9.86cB	30.2dA
FT-BHO	66.3bB	0.967	36.4aB	0.959	12.0dA	33.6cB
Y F-values	492***	-	142***	-	386***	2404***
M F-values	252***	-	187***	-	188***	1315***
Y x M F-values	35.5***	-	14.5***	-	58.8***	673***

Half-lives: $t_{1/2\ 80\%}$ in soils at 80% field water capacity; $t_{1/2\ 1:1.25}$ in soils with 1:1.25 (w/v) (soil/water) moisture content. DHAT, total dehydrogenase activity considering all the incubation times in soils conditioned to 80% field capacity and 1:1.25 (w/v) (soil/water) moisture content. The data presented are mean values. ANOVA factors are: Y, year; M, management regime; Y × M, interaction year × management regime; F-values indicate the significance levels **p*< 0.05, ***p*< 0.01, and ****p*< 0.001, respectively, and NS: not significant. Different letters indicate significant differences (*p*< 0.05) between management regimes in the same year (lowercase letters) and between years within the same management regime (uppercase letters).

Table 4

Effect of different management regimes on bispyribac-sodium leaching parameters.

		Initial Pore volume†	Max. Concentration leached (μM)	Total leached (%)	Total extracted (%)	Not recovered (%)
2018						
SNT		0.768bB	1.35cA	57.4dA	5.60aA	37.0aA
SNT-BHO		0.417aA	0.699abA	54.4dA	2.81aA	42.8aB
ST		1.16cB	1.03bcA	58.3dA	7.42aA	34.3aB
ST-BHO		0.770bA	0.967abcA	50.1cA	4.01aA	45.9bB
FT		1.14cB	0.837abA	44.6bA	1.46aA	53.9cB
FT-BHO		0.744bB	0.571aA	38.3aA	2.51aA	59.2cB
2019						
SNT		0.357aA	0.991aA	62.2cA	12.6aA	25.2aA
SNT-BHO		0.675bB	1.09aA	62.1cB	7.24aA	30.6aA
ST		0.690bA	1.05aA	70.4dB	7.64aA	22.0aA
ST-BHO		0.667bA	0.998aA	63.6cB	4.99aA	31.4aA
FT		0.657bA	0.955aA	58.1bB	4.92aA	37.0abA
FT-BHO		0.343aA	0.850aA	50.3aB	6.13aA	43.5bA
Y	F-values	523***	0.778NS	251***	0.969NS	55.1***
M	F-values	162***	3.80*	85.9***	1.17NS	18.6***
Y x M	F-values	103***	1.33NS	4.64*	1.20NS	1.37NS

The ANOVA factors are: Y, year; M, management regime; Y × M, interaction year × management regime; F-values indicate the significance levels *$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$, respectively, and NS: not significant. Different letters indicate significant differences ($p < 0.05$) between management regimes in the same year (lowercase letters) and between years within the same management regime (uppercase letters).

†Pore volume for initiation of the herbicide's leaching.

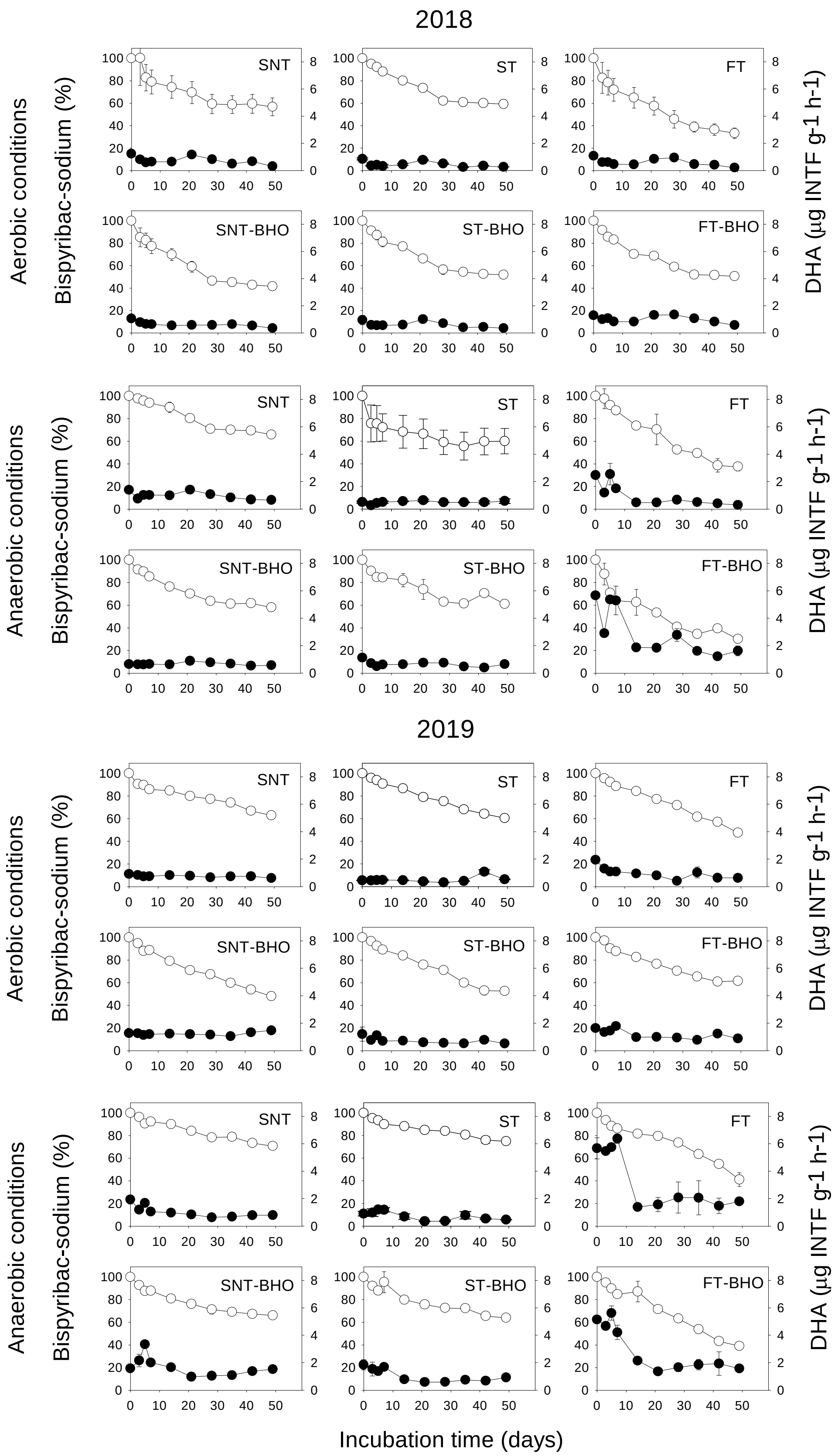

Fig. 1. Effect of different management regimes on dehydrogenase activity (●) and bispyribac-sodium dissipation (○). Vertical bars representing one standard error of the mean were smaller than the symbols in most cases. Treatments are: no-tillage and sprinkler irrigation without (SNT) or with biochar application (SNT-BHO); conventional tillage and sprinkler irrigation without (ST) or with biochar application (ST-BHO); continuous flooding irrigation and tillage without (FT) or with biochar application (FT-BHO).

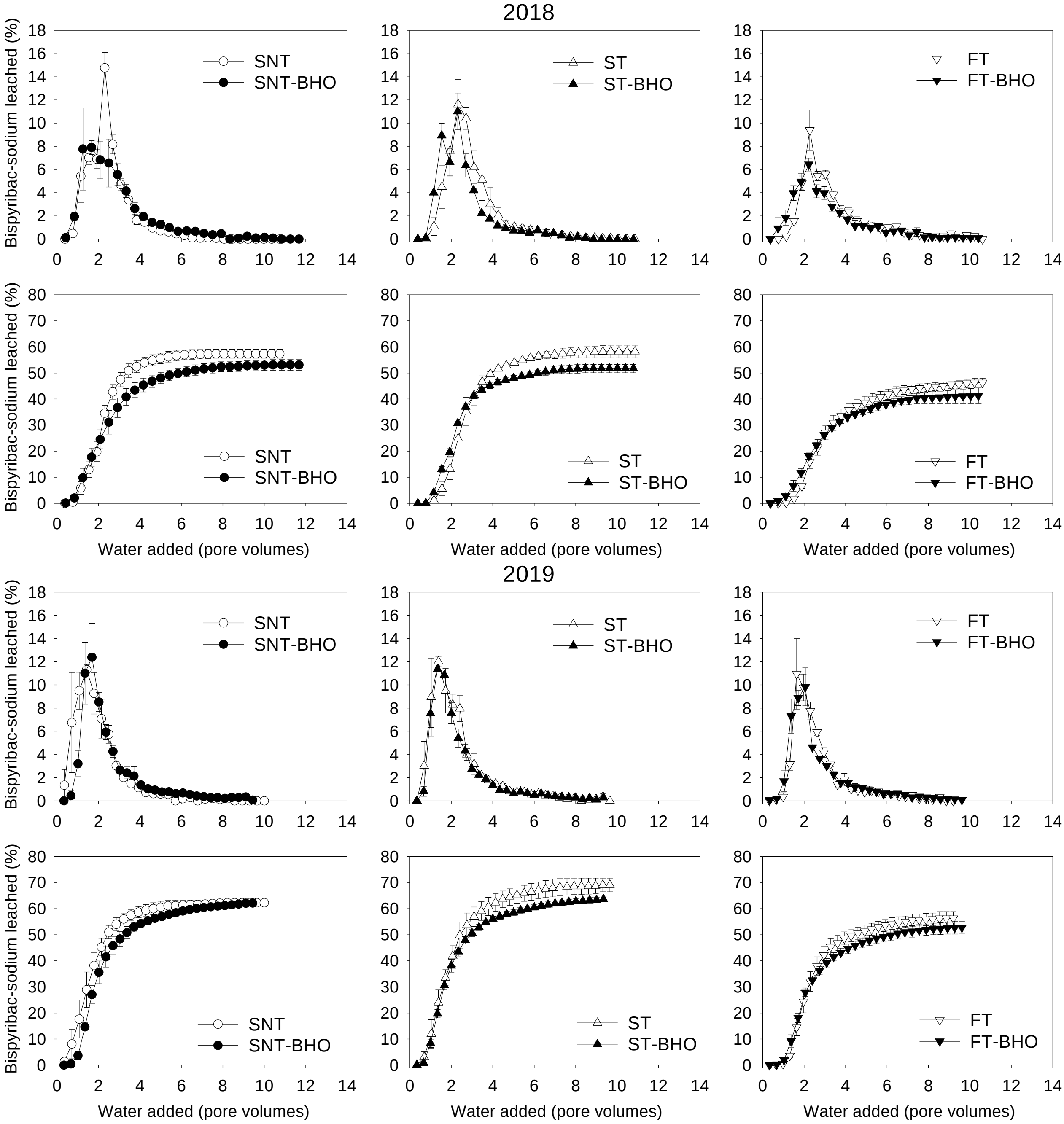

Fig. 2. Effect of different management regimes on the relative (above) and cumulative (below) breakthrough curves of bispyribac-sodium. Vertical bars represent one standard error of the mean. Treatments are: no-tillage and sprinkler irrigation without (SNT) or with biochar application (SNT-BHO); conventional tillage and sprinkler irrigation without (ST) or with biochar application (ST-BHO); continuous flooding irrigation and tillage without (FT) or with biochar application (FT-BHO).

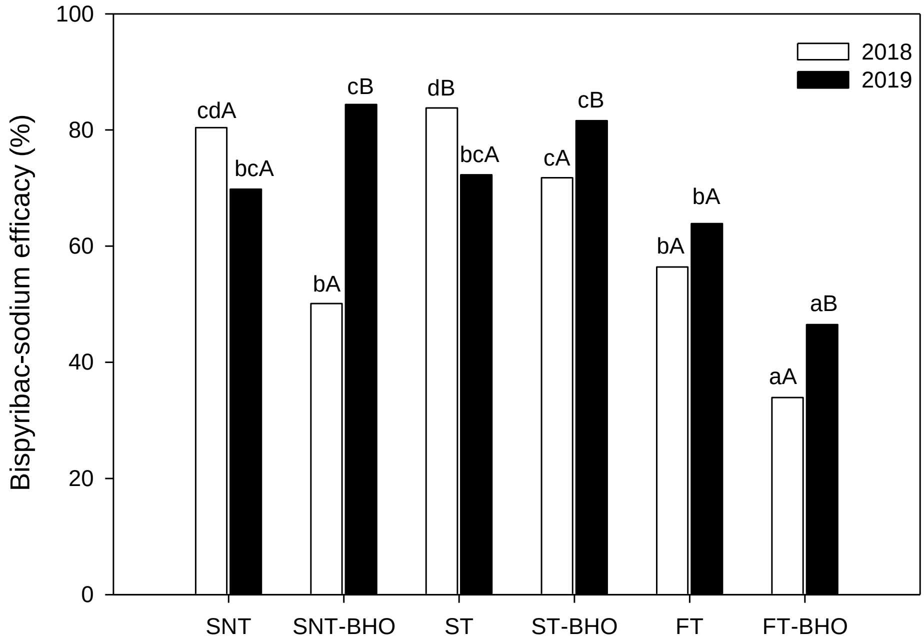

Fig. 3. Effect of different management regimes on bispyribac-sodium efficiency against *Echinochloa crus-galli* L. Beauv. Treatments are: sprinkler irrigation and no-tillage without (SNT) or with biochar application (SNT-BHO); sprinkler irrigation and conventional tillage without (ST) or with biochar application (ST-BHO); traditional flooding irrigation and tillage without (FT) or with biochar application (FT-BHO).