Effects of Strain, Casing-Layer Thickness, and Molybdenum on Yield, Biological Efficiency, and Fruiting-Body Morphology of *Agaricus bisporus*

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Abstract

A cultivation experiment was conducted during the 2025-2026 production season at the Mushroom Research Station, Department of Horticulture and Landscape Engineering, College of Agriculture, Diyala University, Iraq, to evaluate the effects of strain, casing-layer thickness, and molybdenum application on the productivity and fruiting-body morphology of *Agaricus bisporus*. The study was conducted as a 2×3×3 factorial experiment in a completely randomized design with three replicates. The treatments consisted of a white strain (V1) and a brown strain (V2), three peat-moss casing-layer thicknesses (3, 5, 7 cm), and three molybdenum levels (0, 60, 120 mg Mo experimental unit^{-1}) . The evaluated traits were recorded over the first three flushes. Strain V2 produced higher total yield, biological efficiency, and mean fruiting-body weight , reaching 5081.01 g experimental unit^{-1} , 85.77% , and 29.34 g , respectively ,whereas V1 produced a greater number of fruiting bodies (210.82 experimental unit^{-1}). A 5-cm casing layer produced the highest total yield (4985.60 g experimental unit^{-1}), biological efficiency (84.16%) , and fruiting-body number (216.00 experimental unit^{-1}), whereas the 3-cm casing layer produced the highest mean fruiting-body weight (28.32 g). The response to molybdenum varied among traits, the control treatment produced the highest yield and biological efficiency, 60 mg Mo was more favorable for mean fruiting-body weight, and 120 mg Mo produced the highest fruiting-body number. The V2C1M0 combination recorded the highest numerical total yield (5662.90 g experimental unit^{-1}) and biological efficiency (94.66%) , whereas V1C2M120 produced the greatest number of fruiting bodies (310.00 experimental unit^{-1}). Pearson correlation analysis showed a significant negative correlation between fruiting-body number and mean fruiting-body weight ($r = -0.674$, $P \leq 0.001$) and a significant positive correlation between mean fruiting-body weight and total yield ($r = 0.511$, $P \leq 0.001$). Overall , strain and casing-layer thickness clearly influenced production performance, whereas the response to molybdenum depended on the trait evaluated .

Keywords: button mushroom, peat moss , fruiting-body number, mean fruiting-body weight , crop partitioning.

Introduction

Agaricus bisporus is among the most widely cultivated edible mushrooms and is an important crop in intensive mushroom production. Commercial cultivation relies on a composted, heat-treated substrate that is colonized by mycelium before a casing layer is applied to create the conditions required for primordium formation and crop development. Successful production therefore depends on coordinated management of the fungal material, compost , casing layer, water, temperature , relative humidity, and ventilation [1, 2].

Genetic background contributes substantially to variation in *A. bisporus* performance. Yield, fruiting-body number, individual fruiting-body weight, cap colur, and several quality traits differ among genotypes, and quantitative-trait studies have shown that these characteristics are under genetic control to different degrees and may respond differently to the same production environment [3, 4] .

The casing layer is essential to *A. bisporus* production because it provides the immediate environment in which the crop shifts from vegetative growth to fruiting. It stores and redistributes water, maintains pore space and

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gas exchange, supports an active microbial community, and influences the sites at which primordia develop. Changes in casing material, physical properties, or thickness can therefore alter yield, fruiting-body size, water relations, and the timing of crop development [5–8] .

Evidence from studies conducted directly on *A. bisporus* shows that strain choice and casing management can alter different components of crop development. Screening trials have reported variation in yield and fruiting-body quality among strains and casing conditions [9], while casing depth and physicochemical properties have been linked to yield and water transfer to developing mushrooms [10 , 11]. Substantial productivity differences have also been documented among *A. bisporus* strains [12] , and micronutrient supplementation through the casing layer, including molybdenum, has been examined as a means of modifying fruiting-body composition [13]. Together , these studies provide a direct basis for evaluating strain, casing thickness, and mineral supplementation within the same cultivation system.

Mineral nutrition is another potential source of variation in crop response. Molybdenum becomes biologically active after incorporation into molybdenum-containing cofactors required by several oxidation-reduction enzymes, including enzymes associated with nitrogen metabolism [14] . Fungal nitrate reductase is molybdenum-cofactor dependent [15] . However, micronutrient experiments with *A. bisporus* have shown that production responses depend on the element and application rate and do not necessarily improve as supplementation increases [16]. Molybdenum therefore has a plausible physiological role, but additional supply cannot be assumed to enhance production.

Strain effects, casing management, and mineral supplementation have each been studied in *A. bisporus*, but information on their combined effects remains limited, particularly when molybdenum is applied through casing layers of different thicknesses. Because the response to a mineral treatment may depend on both the fungal material and the physical environment of the casing, a factorial approach can reveal interactions that separate-factor studies may overlook [3, 8, 16]. This study therefore evaluated two *A. bisporus* strains, three casing-layer thicknesses, and three molybdenum levels, alone and in combination, for their effects on total yield, biological efficiency, fruiting-body number, mean fruiting-body weight, and selected morphological traits.

Materials and Methods

Experimental site and production-room preparation

The experiment was conducted during the 2025-2026 production season at the Mushroom Research Station, Department of Horticulture and Landscape Engineering, College of Agriculture, Diyala University, Iraq. Cultivation was carried out in a 4×7 m controlled production room. Before cultivation, the room and production equipment were cleaned and disinfected with a 4% formalin solution prepared from commercial formalin . The room remained closed for 3 d and was then thoroughly ventilated. Temperature and relative humidity were monitored electronically; an inverter air-conditioning unit controlled temperature, and mechanical ventilation was used to renew the air and limit gas accumulation.

Compost preparation and pasteurization

Compost was prepared from approximately 900 kg of wheat straw, 520 kg of poultry manure, 70 kg of agricultural gypsum, and 9 kg of urea, providing about 1.5 t of starting material. The straw was moistened and mixed with poultry manure, gypsum, and urea, and water was added gradually until moisture reached approximately 60–70% . The pile was fermented for 14 d, turned every 3 d, and watered when necessary; internal temperature ranged from 60 to 70 ° C. After fermentation, the compost was steam-pasteurized at 58–60 °C for 6-8 h, then ventilated during cooling and conditioning until its temperature fell to about 25 °C before spawning. The preparation procedure was adapted from Hassan et al. [18] and was consistent with established principles of *A. bisporus* compost production [17].

Mushroom strains

Spawn of two phenotypically distinct *A. bisporus* strains was obtained from Al-Wadaq Mushroom Production Company. The strain producing white fruiting bodies was designated V1, and the strain producing brown fruiting bodies was designated V2. The supplier identified the materials only as white and brown strains and did not provide commercial strain codes. Species identity was subsequently confirmed by ITS sequencing: V1 showed 100% identity to an A. bisporus reference sequence (PP140826.1), whereas V2 showed 99.33% identity to an A. bisporus reference sequence (PP140817.1). These accession numbers refer to the closest matching reference sequences and were not assigned to the strains used in this study.

Experimental design and treatment application

The experiment was arranged as a 2×3×3 factorial in a completely randomized design with three replicates per treatment combination. The factors were strain (V1 and V2), casing-layer thickness (3, 5, 7 cm), and molybdenum level (0, 60, 120 mg Mo experimental unit^{-1}), resulting in 18 treatment combinations and 54 experimental units. Each experimental unit consisted of one perforated black polyethylene bag measuring 60×40×15 cm and containing approximately 18 kg of wet compost. After the compost cooled to about 25 °C, spawn was mixed uniformly with the compost at 2% of wet compost weight on January 21, 2026. The bags were incubated until complete mycelial colonization at 23±2 °C and room-air relative humidity of at least 70% . The relative-humidity value refers to the air surrounding the cultivation bags and not to compost moisture.

Casing, molybdenum application, and fruiting conditions

After the compost was fully colonized, the upper portion of each bag was opened and peat moss obtained from Al-Wadaq Mushroom Production Company was applied at a thickness of 3, 5, or 7 cm according to treatment. A wooden frame was used to maintain uniform casing thickness and distribution. Three days after casing, ammonium molybdate was used to supply 0, 60, or 120 mg elemental Mo per experimental unit. The assigned dose was dissolved in the same volume of irrigation water for all treatments, and the entire solution was distributed uniformly over the casing surface of each experimental unit. Irrigation was continued as needed to maintain suitable casing moisture. During casing colonization, temperature was maintained at 24±2 °C and room-air relative humidity at no less than 70%, with light ventilation. When visible mycelial aggregates developed beneath the casing surface, temperature was gradually reduced to about 16 °C and room-air relative humidity was raised to approximately 80% to encourage pinning. As fruiting bodies developed and before harvest, room-air relative humidity was returned to approximately 70%, while temperature was maintained at 16-18 °C , with continued ventilation to limit carbon dioxide accumulation . Baseline molybdenum concentration in the compost and peat-moss casing was not determined before treatment; therefore, the levels of 0, 60, and 120 mg Mo experimental unit^{-1} refer to the amount of elemental Mo added experimentally, not to total molybdenum concentration in the cultivation medium.

Harvest and measurements

Harvesting began approximately 5 days after pin formation. Production and morphological measurements were based on the first three flushes, and each experimental unit was recorded separately. Fruiting-body number was calculated as the cumulative number harvested across the three flushes, and total yield as their cumulative fresh weight. Mean fruiting-body weight was calculated separately for each experimental unit by dividing its total yield by its total number of fruiting bodies; treatment means were then calculated from the replicate-level values. Biological efficiency (BE) was calculated as fresh fruiting-body yield divided by dry substrate weight and multiplied by 100, following the standard definition used for Agaricus production [19] . Dry substrate weight was estimated from the dry-matter proportion of a representative compost sample

collected at the beginning of cultivation. For morphological measurements, five fruiting bodies were used from each experimental unit. Stipe length was measured with a graduated ruler, whereas cap diameter , stipe diameter, and cap thickness were measured with a digital caliper. All morphological measurements are reported in centimeters. The reported fruiting-body number is therefore cumulative across the first three flushes and does not represent the number of mushrooms present simultaneously on the bag surface.

Statistical analysis

Data were analyzed with SAS software for the 2×3×3 factorial experiment in a completely randomized design. Treatment means were compared using Duncan's multiple range test at $P \leq 0.05$ [20]. Statistical interpretation followed the Duncan letters shown in the tables: means sharing at least one letter were considered not significantly different, whereas means with no letter in common were considered significantly different at $P \leq 0.05$. Pearson correlation coefficients were also calculated to examine relationships among production and fruiting-body morphological traits, with significance evaluated at $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$.

Results

Production traits

The two strains showed significantly different production patterns (Table 1). V2 had higher total yield, biological efficiency, and mean fruiting-body weight, reaching 5081.01 g experimental unit^{-1}, 85.77%, and 29.34 g, respectively. In contrast, V1 produced more fruiting bodies, averaging 210.82 experimental unit^{-1} compared with 176.56 for V2. Thus, the higher yield of V2 coincided mainly with greater individual fruiting-body weight rather than a higher fruiting-body count.

Casing-layer thickness significantly affected all four production traits (Table 1). The 5-cm casing layer produced the highest total yield, biological efficiency, and fruiting-body number, with means of 4985.60 g experimental unit^{-1}, 84.16%, and 216.00 experimental unit^{-1}, respectively. The 3-cm layer produced the highest mean fruiting-body weight (28.32 g), whereas the 7-cm layer gave the lowest total yield, biological efficiency, and mean fruiting-body weight.

The molybdenum response depended on the trait measured (Table 1). The control produced the highest total yield and biological efficiency, while 60 and 120 mg Mo did not differ significantly for these traits. Fruiting-body number was highest at 120 mg Mo, followed by the control and 60 mg Mo, whereas mean fruiting-body weight was highest at 60 mg Mo, followed by the control and 120 mg Mo. Thus, no single level optimized all production components.

Two-way interactions were trait-dependent (Table 1). For strain × casing thickness, V2C1 and V2C2 gave the highest yield and biological efficiency, V1C2 the highest fruiting-body number, and V2C1 the highest mean fruiting-body weight. For strain × molybdenum, V2M0 had the highest numerical yield and biological efficiency, whereas V1M120 produced the most fruiting bodies. For casing thickness × molybdenum, C2M120 had the highest numerical yield, biological efficiency, and fruiting-body number, while C2M60 had the highest mean fruiting-body weight.

The three-way interaction also varied among traits (Table 1). V2C1M0 had the highest numerical total yield (5662.90 g experimental unit^{-1}) and biological efficiency (94.66%), although several V2 combinations were statistically similar. V1C2M120 produced the most fruiting bodies (310.00 experimental unit^{-1}), while the greatest mean fruiting-body weights occurred in V2C1M120 and V2C2M60.

Table 1. Effects of mushroom strain, casing-layer thickness, molybdenum level, and their interactions on production traits of *Agaricus bisporus*.

Mean fruiting-body weight (g)	Number of fruiting bodies (experimental unit^{-1})	Biological efficiency (%)	Total yield (g experimental unit^{-1})	Treatment
Single factors				
20.64 B	210.82 A	71.40 B	4190.74 B	V1
29.34 A	176.56 B	85.77 A	5081.01 A	V2
28.32 A	168.22 C	79.00 B	4682.12 B	C1 (3 cm)
24.48 B	216.00 A	84.16 A	4985.60 A	C2 (5 cm)
22.17 C	196.83 B	72.61 C	4239.91 C	C3 (7 cm)
24.35 B	203.61 B	81.38 A	4837.16 A	M0 (0 mg)
27.50 A	165.00 C	76.11 B	4490.36 B	M60 (60 mg)
23.12 C	212.44 A	78.27 B	4580.11 B	M120 (120 mg)
Two-way interaction: V × C				
22.02 cd	175.44 bc	65.33 d	3814.40 d	V1C1
20.24 d	243.56 a	79.66 b	4720.40 b	V1C2
19.65 d	213.44 ab	69.22 cd	4037.50 cd	V1C3
34.63 a	161.00 c	92.66 a	5549.90 a	V2C1
28.72 b	188.44 bc	88.66 a	5250.80 a	V2C2
24.68 c	180.22 bc	76.00 bc	4442.40 bc	V2C3
Two-way interaction: V × M				
20.29 c	214.56 b	71.77 cd	4258.40 cd	V1M0
24.54 b	158.33 c	66.66 d	3889.60 d	V1M60
17.08 c	259.56 a	75.77 bcd	4424.20 cd	V1M120
28.42 ab	192.67 bc	91.00 a	5415.90 a	V2M0
30.47 a	171.67 c	85.55 ab	5091.10 ab	V2M60
29.15 a	165.33 c	80.77 bc	4736.00 bc	V2M120
Two-way interaction: C × M				
28.57 abc	165.33 d	79.50 abc	4738.20 abc	C1M0
28.95 ab	168.83 cd	81.33 abc	4865.00 abc	C1M60
27.45 abcd	170.50 cd	76.16 abc	4443.20 abc	C1M120
22.13 bcd	229.83 ab	84.50 ab	5008.70 ab	C2M0
30.65 a	156.83 d	80.16 abc	4744.80 abc	C2M60
20.67 d	261.33 a	87.83 a	5203.30 a	C2M120
22.36 bcd	215.67 bc	80.16 abc	4764.50 abc	C3M0
22.91 bcd	169.33 cd	66.83 c	3861.40 c	C3M60
21.23 cd	205.50 bcd	70.83 bc	4093.90 bc	C3M120
Three-way interaction: V × C × M				
23.74 de	161.00 gh	64.33 fg	3813.50 g	V1C1M0
25.07 cd	172.00 g	72.66 de	4298.10 f	V1C1M60
17.24 f	193.33 f	59.00 gh	3331.50 h	V1C1M120
19.02 f	253.66 c	81.00 c	4818.50 cde	V1C2M0
25.06 cd	167.00 g	70.66 e	4179.30 fg	V1C2M60
16.66 f	310.00 a	87.33 b	5163.40 bcd	V1C2M120
18.11 f	229.00 d	70.00 ef	4143.20 fg	V1C3M0
23.49 de	136.00 i	56.66 h	3191.30 h	V1C3M60

Mean fruiting-body weight (g)	Number of fruiting bodies (experimental unit⁻ ¹)	Biological efficiency (%)	Total yield (g experimental unit⁻ ¹)	Treatment
17.36 f	275.33 b	81.00 c	4777.90 de	V1C3M120
33.40 b	169.67 g	94.66 a	5662.90 a	V2C1M0
32.82 b	165.67 g	90.00 ab	5431.80 ab	V2C1M60
37.66 a	147.67 hi	93.33 ab	5554.90 ab	V2C1M120
25.25 cd	206.00 ef	88.00 b	5198.90 bc	V2C2M0
36.24 a	146.67 hi	89.66 ab	5310.30 ab	V2C2M60
24.69 cde	212.67 de	88.33 ab	5243.20 ab	V2C2M120
26.61 c	202.33 ef	90.33 ab	5385.90 ab	V2C3M0
22.34 e	202.67 ef	77.00 cd	4531.40 ef	V2C3M60
25.10 cd	135.67 i	60.66 gh	3409.90 h	V2C3M120

V1 = white strain; V2 = brown strain; C1, C2, and C3 = 3, 5, and 7 cm casing layers, respectively; M0, M60, and M120 = 0, 60, and 120 mg Mo experimental unit⁻ ¹, respectively. Within each trait and effect section, means sharing at least one letter are not significantly different, whereas means with no letter in common differ significantly according to Duncan's multiple range test at $P \leq 0.05$. Uppercase letters indicate comparisons among single-factor means, whereas lowercase letters indicate comparisons among interaction means.

Fruiting-body morphological traits

Cap thickness did not differ significantly between the two strains (Table 2). The 3- and 5-cm casing layers produced greater cap thickness than the 7-cm layer. The control exceeded the 120-mg Mo treatment, whereas 60 mg Mo did not differ significantly from either. Several interaction means differed significantly, with the highest three-way values recorded for V1C1M60, V2C2M120, V2C2M0, and V1C1M0.

V1 had a significantly longer stipe than V2, with means of 2.41 and 1.84 cm, respectively (Table 2). No significant differences were detected among casing-layer thicknesses or molybdenum levels for the main effects. The interaction means differed significantly, with V1C3M0 recording the longest stipe and V2C2M60 the shortest.

V2 had a significantly greater stipe diameter than V1, averaging 1.74 versus 1.47 cm (Table 2). The 3- and 5-cm casing layers exceeded the 7-cm layer, while molybdenum levels did not differ significantly. Within the three-way interaction, V2C2M0 recorded the greatest stipe diameter and V1C3M120 the lowest.

Cap diameter did not differ significantly between strains or among casing-layer thicknesses (Table 2) . The control produced a larger cap diameter than the 60- and 120-mg Mo treatments, which did not differ significantly from each other. Within the three-way interaction, V2C2M0 recorded the greatest cap diameter and V1C3M120 the lowest.

Relationships among production and morphological traits

Pearson correlation analysis revealed several relationships among production and morphological traits (Table 3). Fruiting-body number was negatively correlated with mean fruiting-body weight ($r = -0.674$, $P \leq 0.001$) and stipe diameter ($r = -0.370$, $P \leq 0.01$), but positively correlated with stipe length ($r = 0.349$, $P \leq 0.01$). Mean fruiting-body weight was positively correlated with total yield ($r = 0.511$, $P \leq 0.001$) and stipe diameter ($r = 0.497$, $P \leq 0.001$), and negatively correlated with stipe length ($r = -0.470$, $P \leq 0.001$). Total yield and biological efficiency were strongly correlated ($r = 0.996$, $P \leq 0.001$), as expected because biological efficiency is calculated from yield relative to dry substrate weight. Cap diameter was positively correlated with cap thickness, and cap thickness was positively correlated with stipe diameter.

Discussion

Strain-dependent allocation between fruiting-body number and weight

The two strains differed in how crop production was distributed between fruiting-body number and individual weight. V1 produced more fruiting bodies, whereas V2 produced fewer but heavier fruiting bodies, resulting in higher total yield and biological efficiency for V2. Genetic variation in *A. bisporus* has been reported for yield, fruiting-body number, individual weight, and related quality traits [3, 4], and comparisons among cultivated strains have also shown marked differences in productivity and fruiting-body size [21, 22]. These findings confirm that strain choice can strongly influence crop structure, although the present comparison applies specifically to V1 and V2 and should not be generalized to all white and brown strains.

Correlation between yield components and crop allocation

The correlation pattern supports the contrasting production behavior of the two strains. The strong negative relationship between fruiting-body number and mean fruiting-body weight indicates a number–weight trade-off: treatments producing more fruiting bodies tended to produce lighter individual mushrooms. Mean fruiting-body weight, in contrast, was positively associated with total yield, whereas the relationship between fruiting-body number and total yield was not significant. This helps explain why V2 achieved the higher yield despite producing fewer fruiting bodies. Heavier fruiting bodies were also associated with greater stipe diameter and shorter stipes, a pattern consistent with the morphology recorded for V2. These coefficients describe associations within the experimental dataset and do not, by themselves, establish direct causal relationships.

Table 2. Effects of mushroom strain, casing-layer thickness, molybdenum level, and their interactions on fruiting-body morphological traits of *Agaricus bisporus*.

Cap diameter (cm)	Stipe diameter (cm)	Stipe length (cm)	Cap thickness (cm)	Treatment
Single factors				
5.00 A	1.47 B	2.41 A	2.52 A	V1
5.11 A	1.74 A	1.84 B	2.59 A	V2
5.05 A	1.69 A	1.97 A	2.66 A	C1 (3 cm)
5.19 A	1.65 A	2.05 A	2.62 A	C2 (5 cm)
4.92 A	1.47 B	2.35 A	2.38 B	C3 (7 cm)
5.37 A	1.63 A	2.29 A	2.64 A	M0 (0 mg)
4.93 B	1.59 A	1.97 A	2.54 AB	M60 (60 mg)
4.87 B	1.58 A	2.11 A	2.48 B	M120 (120 mg)
Two-way interaction: V × C				
5.11 b	1.60 bc	2.23 ab	2.73 a	V1C1
4.81 b	1.48 cd	2.25 ab	2.48 bc	V1C2
5.09 b	1.31 d	2.74 a	2.34 c	V1C3
5.00 b	1.77 ab	1.71 b	2.60 ab	V2C1
5.58 a	1.82 a	1.85 b	2.76 a	V2C2
4.76 b	1.62 abc	1.96 b	2.43 bc	V2C3
Two-way interaction: V × M				
5.32 ab	1.53 bc	2.57 a	2.59 ab	V1M0
4.99 abc	1.49 bc	2.26 abc	2.61 a	V1M60
4.69 c	1.37 c	2.39 ab	2.35 b	V1M120
5.42 a	1.73 ab	2.01 abc	2.70 a	V2M0
4.86 bc	1.69 ab	1.68 c	2.46 ab	V2M60
5.06 abc	1.79 a	1.83 bc	2.62 a	V2M120
Two-way interaction: C × M				
5.35 a	1.74 a	2.32 a	2.79 a	C1M0
4.91 ab	1.67 ab	1.84 a	2.69 ab	C1M60
4.91 ab	1.64 ab	1.76 a	2.51 abc	C1M120
5.43 a	1.77 a	1.95 a	2.68 ab	C2M0
4.96 ab	1.63 ab	1.85 a	2.52 abc	C2M60
5.18 ab	1.56 ab	2.34 a	2.66 ab	C2M120
5.34 a	1.38 b	2.60 a	2.47 bc	C3M0
4.90 ab	1.47 ab	2.22 a	2.40 bc	C3M60
4.53 b	1.54 ab	2.23 a	2.28 c	C3M120
Three-way interaction: V × C × M				
5.30 abcd	1.66 abcdef	2.60 abc	2.88 a	V1C1M0
5.15 bcde	1.64 abcdef	2.14 bcd	2.92 a	V1C1M60
4.87 cde	1.50 bcdef	1.96 bcd	2.41 bc	V1C1M120
4.83 cde	1.59 abcdef	1.83 bcd	2.46 bc	V1C2M0
4.80 cde	1.50 bcdef	2.32 abcd	2.57 abc	V1C2M60
4.79 cde	1.36 def	2.58 abc	2.42 bc	V1C2M120
5.84 ab	1.34 ef	3.27 a	2.43 bc	V1C3M0
5.02 cde	1.35 ef	2.31 abcd	2.35 bc	V1C3M60
4.40 e	1.25 f	2.64 ab	2.23 c	V1C3M120
5.40 abcd	1.83 abc	2.04 bcd	2.71 ab	V2C1M0

Cap diameter (cm)	Stipe diameter (cm)	Stipe length (cm)	Cap thickness (cm)	Treatment
4.67 de	1.70 abcde	1.53 cd	2.47 bc	V2C1M60
4.93 cde	1.79 abc	1.57 cd	2.61 ab	V2C1M120
6.03 a	1.95 a	2.07 bcd	2.89 a	V2C2M0
5.13 bcde	1.77 abcd	1.38 d	2.47 bc	V2C2M60
5.58 abc	1.75 abcde	2.10 bcd	2.91 a	V2C2M120
4.84 cde	1.42 cdef	1.93 bcd	2.51 bc	V2C3M0
4.78 cde	1.60 abcdef	2.13 bcd	2.44 bc	V2C3M60
4.66 de	1.84 ab	1.82 bcd	2.34 bc	V2C3M120

V1 = white strain; V2 = brown strain; C1, C2, and C3 = 3, 5, and 7 cm casing layers, respectively; M0, M60, and M120 = 0, 60, and 120 mg Mo experimental unit^{-1}, respectively. Within each trait and effect section, means sharing at least one letter are not significantly different, whereas means with no letter in common differ significantly according to Duncan's multiple range test at $P \leq 0.05$. Uppercase letters indicate comparisons among single-factor means, whereas lowercase letters indicate comparisons among interaction means.

Table 3. Pearson correlation matrix among production and fruiting-body morphological traits of *Agaricus bisporus*.

7	6	5	4	3	2	1	Trait
						—	1. Number of fruiting bodies
					—	−0.674***	2. Mean fruiting-body weight
				—	0.511***	0.265	3. Total yield
			—	0.996***	0.512***	0.264	4. Biological efficiency
		—	0.097	0.101	0.089	−0.077	5. Cap diameter
	—	0.559***	0.218	0.229	0.238	−0.150	6. Cap thickness
—	0.544***	0.301*	0.276*	0.268	0.497***	−0.370**	7. Stipe diameter
−0.164	0.279 *	0.306*	−0.227	−0.215	−0.470***	0.349**	8. Stipe length

Values below the diagonal are Pearson correlation coefficients. *, **, and *** indicate significance at $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; coefficients without asterisks are not significant ($P>0.05$).

Casing-layer thickness and production balance

Casing layer thickness clearly affected crop structure. The 5-cm layer provided the best production balance, giving the highest yield, biological efficiency, and fruiting-body number, whereas the 3-cm layer favored greater individual fruiting-body weight. Increasing thickness to 7 cm did not improve production and was associated with the lowest yield, biological efficience , and mean fruiting-body weight. This response is consistent with the role of the casing layer as a water reservoir, a porous interface for gas exchange, and a biologically active zone for primordium formation [5, 6]. Its physical properties influence water relations and crop performance [23, 24], and studies of casing thickness have reported corresponding changes in *A. bisporus* yield and related traits [8]. Recent work has also shown that developing fruiting bodies obtain water from both the casing layer and compost, with a direct contribution from the casing [25]. The

advantage of the 5-cm layer in this experiment may therefore reflect a favorable balance between water supply and aeration. However, casing water potential, porosity, and microbial composition were not measured, so the underlying mechanism cannot be identified directly from the present data.

Response of production components to molybdenum

Molybdenum did not produce a uniform positive response as the application level increased. The control gave the highest total yield and biological efficiency, 60 mg Mo favored mean fruiting-body weight, and 120 mg Mo favored fruiting-body number . Cap diameter was also greater in the control than at either supplemented level. These contrasting responses suggest that molybdenum affected specific components of crop growth rather than stimulating production as a whole. Physiologically, molybdenum is incorporated into cofactors required by several redox enzymes, including fungal nitrate reductase [14, 15]. However, this study did not measure molybdenum accumulation, its availability in the casing layer, nitrogen assimilation, or enzyme activity. The most defensible interpretation is therefore that the response depended on both application level and the trait considered, consistent with previous reports that micronutrient effects in *A. bisporus* vary with the element and application rate [16].

Factor interactions and practical implications

The interaction means show that the preferred treatment depends on the production objective. V2C1M0 recorded the highest numerical yield and biological efficiency, whereas V1C2M120 produced the greatest number of fruiting bodies, and V2C1M120 and V2C2M60 produced the highest mean fruiting-body weights. Morphologically, V2 generally formed shorter, thicker stipes. Cap thickness did not differ between strains, and cap diameter was unaffected by strain or casing-layer thickness at the main-effect level. Thus, no single treatment combination maximized total crop mass, fruiting-body number, individual weight, and morphology simultaneously. Treatment selection should therefore be matched to the production trait of interest rather than based on a single overall ranking.

Conclusion

Under the conditions of this study, strain and casing-layer thickness played clear roles in shaping *A. bisporus* productivity. V2 produced fewer but heavier fruiting bodies and achieved higher total yield and biological efficiency than V1, whereas V1 produced more fruiting bodies. A 5-cm casing layer provided the best production balance, while a 3-cm layer favored individual fruiting-body weight. Molybdenum supplementation did not provide a consistent yield advantage because responses varied among traits. The negative correlation between fruiting-body number and mean weight confirmed a clear number-weight trade-off, while the positive relationship between mean weight and total yield highlighted the contribution of individual fruiting body weight to crop mass. Treatment choice should therefore be guided by the intended production objective rather than by the assumption that increasing molybdenum supply will improve overall performance.

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Conflict of Interest

The authors declare no conflict of interest.

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