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Influence of Cold Exposure for Different Durations on Laboratory-Reared *Habrobracon hebetor* (Say) (Hymenoptera: Braconidae)

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Abstract: Biological control by releasing a large number of parasitoids has been an effective strategy for coping with stored-product pest insects. *Habrobracon hebetor* (Say) (Hymenoptera: Braconidae) has strong control capabilities over Lepidoptera pests. Exploring the optimum storage temperature, life stage, and cold storage period of *H. hebetor* is of great importance for the utilization of parasitoids. In this context, the survival, parasitism, and fecundity of *H. hebetor* were evaluated after 10, 20, 30, 40, 50, and 60 d of exposure at −5, 0, 5, 10, and 15 °C for *H. hebetor* eggs, larvae, pupae, and adults, and the survival, parasitism, and fecundity of *H. hebetor* individuals that had been maintained at normal rearing condition were taken as a control. The cold exposure duration dramatically affected the development and survival of eggs, larvae, and pupae of *H. hebetor*, regardless of the temperatures tested. *Habrobracon hebetor* eggs, larvae, and pupae failed to develop into the next life stage at −5, 0, and 5 °C. *Habrobracon hebetor* eggs, larvae, pupae, and adults failed to survive after 10 d exposure at −5 and 0 °C. The parasitism rate, fecundity and oviposition duration of *H. hebetor* adults that originated from eggs, larvae, pupae, and adults after different cold storage durations markedly decreased with increasing cold storage duration. The highest parasitism rate of adults was 34.12% after exposure at 5 °C for 10 d, which was not significantly different from the control (31.86%). The maximum level of egg production of *H. hebetor* adults developed from initial larvae exposed at 15 °C for 10 d and 20 d were 344.67 and 340.67 eggs/female, respectively, which were not significantly different from the control (392.00 eggs/female). When *H. hebetor* larvae were stored at 15 °C for 10 and 60 d, the oviposition duration of newly emerged adults reached the maximum and minimum levels recorded, with 17.00 and 0.83 d, respectively. These results provide empirical support for the large-scale production and storage of *H. hebetor*.

Keywords: low temperature; survival; parasitism

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1. Introduction

Augmentative release of parasitic wasps has been an important strategy for coping with stored-product pest insects [1]. In this context, the parasitic wasps must be produced shortly before release due to their relatively short life, which inevitably increases the rearing cost of natural enemies and biological control costs [2]. Cold storage may be a useful strategy to store natural enemies on a large scale and for long intervals [3], which ensures a stable supply of sufficient and high quality parasitic wasps whenever they are needed.

Habrobracon hebetor (Say) (Hymenoptera: Braconidae) can effectively parasitize many species of Lepidoptera pests that attack stored cereals, beans, oilseeds, dried fruits, and medicinal materials [4–8]. Several studies have reported the influence of cold exposure on *H. hebetor* lifespan and fertility. The survival of *H. hebetor* pupae decreases when stored at 4 °C for more than 20 d [9]. *Habrobracon hebetor* pupae can be maintained for 15 d at 4 °C and 80% relative humidity [10]. The adults can be stored at 8 °C for approximately 2 months [11]. Storing pupae at 5 ± 1 °C for more than 30 d results in reducing the parental parasitism, but has no impact on their offspring parasitism [12]. A small number of adults of *H. hebetor* die or have deformed wings when stored at 10 °C for more than 30 d. The proportion of newly emerged adults with wing deformities increases after 40 d of cold storage of pupae [13]. When reared and stored at 20 °C for 8 weeks or less, the wasp's developmental duration, survival, and parasitism ability are similar to those of individuals that were reared at 30 °C [14].

To date, most studies have focused on the effects of cold storage on *H. hebetor* pupae or adults, but there is little research on the performance of eggs and larvae after cold storage. Thus, the purpose of this research was to explore the survival, emergence, parasitism, and oviposition duration of *H. hebetor* over a range of exposure intervals and low temperatures for different life stages of the parasitoid. The optimal cold storage temperature, storage duration, and life stage were evaluated, in order to provide the inferences necessary for the large-scale production and release protocols of *H. hebetor*.

2. Materials and Methods

2.1. Experimental Insects

The *Ephestia elutella* (Lepidoptera: Pyralidae) and *H. hebetor* colonies have been maintained in the Stored-products Insect Control Laboratory in Henan University of Technology for more than 5 years. *Ephestia elutella* late-instar larvae were supplied to rear *H. hebetor*. *Ephestia elutella* was reared on a diet (50% wheat bran, 30% corn grit, 10% soybean powder, 5% glycerol, and 5% honey water) at 30 ± 2 °C, 75 ± 5% relative humidity (RH), and 12 h:12 h (Light:Dark). To obtain *E. elutella* late-instar larvae as hosts for raising *H. hebetor*, approximately three hundred newly emerged moths were transferred to 100 g rearing diet for 1 d, then the moths were removed, and the diet was maintained in a culture chamber for 33 d at rearing conditions mentioned above.

Five pairs of *H. hebetor* adults (1-d-old, female:male = 1:1) were released into one plastic box (top diameter: 7.3 cm, bottom diameter: 5.5 cm, and height: 3.5 cm) containing 25 late-instar *E. elutella* larvae. Then, the *H. hebetor* adults were removed from the plastic box after 24 h. There were 3–6 eggs on each *E. elutella* larva. The eggs were maintained for 2, 5, and 10 d at rearing conditions mentioned above. Eggs, larvae and pupae of the parasitoid on *E. elutella* larvae, and *H. hebetor* adults used in the experiments were 1, 2, 3, and 1-d old, respectively. Eggs (1-d old) of the parasitoid were obtained within 1 d after *H. hebetor* laided eggs on *E. elutella* larvae. The larvae of the parasitoid were obtained after *H. hebetor* eggs had hatched on *E. elutella* larvae for 2 d. The pupae of the parasitoid were obtained after *H. hebetor* larvae had pupated on *E. elutella* larvae for 3 d. The adults of the parasitoid were obtained after *H. hebetor* pupae had emerged on *E. elutella* larvae for 1 d. The wasp takes 11.94 ± 0.02 d to complete its life cycle at 30 °C. *Habrobracon hebetor* larvae lived on the host. The life stages of the host larvae were determined by the number of molts.

2.2. Cold Storage Procedure for H. hebetor

Thirty *H. hebetor* eggs, larvae, and pupae on *E. elutella* larvae, female and male adults were randomly selected, respectively, and placed in plastic boxes (top diameter: 6.6 cm,

bottom diameter: 5.4 cm, height: 3.8 cm). Then, the plastic boxes were maintained at −5, 0, 5, 10, and 15 °C, 75 ± 5% RH, and 0 h:24 h (Light:Dark) for 10, 20, 30, 40, 50, and 60 d, respectively. Their life stage and survival were observed after the termination of different cold exposure durations, respectively. After cold exposure durations, all life stages of *H. hebetor* were maintained at rearing conditions mentioned above, and the newly emerged adults were counted. Each mated female wasp was offered daily 50 host larvae until it died. The paralyzed host larvae, and the eggs laid by the female wasps and their oviposition duration were counted and recorded. The survival, emergence, parasitism, and oviposition duration of *H. hebetor* individuals that had been maintained at normal rearing condition were taken as a control. Each experimental treatment was repeated three times. All experimental treatments (5 temperatures × 4 life stages × 6 storage durations = 120 treatment combinations) were tested three times at the same time each.

2.3. Statistics

The number of eggs laid by *H. hebetor* was converted by $\log_{10}(x + 1)$ scale. The percentages of survival and parasitism of *H. hebetor* were converted to arcsine square-root values. Three-way ANOVA analysis with temperature, insect life stage, cold exposure duration as fixed variables was applied to compare the differences among different experimental treatments. The assumptions of data normality were checked before statistics. Repeated measures analysis of variance was conducted by SPSS23.0. A minimum value (0.001) was assigned to each zero value before analysis.

Habrobracon hebetor survival rate and parasitism rate were calculated using the following formulas:

Survival rate (%) = (the total number of newly emerged adult *H. hebetor* or live adult *H. hebetor* after cold exposure/The total number of initial *H. hebetor* individuals at the beginning of cold exposure) × 100

Parasitism rate (%) = (the number of parasitized *E. elutella* late-instar larvae with eggs/The total number of initial *E. elutella* late-instar larvae) × 100

3. Results

3.1. Impacts of Different Low-Temperature Exposure Durations on Different Life Stages of H. hebetor

The different low-temperature exposure durations markedly affected the development of *H. hebetor* (Table 1). The eggs of *H. hebetor* could not develop into larvae at −5, 0, 5, and 10 °C, but they did develop into larvae and pupae after 10 d and 50 d of exposure at 15 °C, respectively. The *H. hebetor* larvae could not develop into pupae at −5, 0, and 5 °C, but they did develop into pupae after 20 d and 10 d of cold storage at 10 and 15 °C, respectively. The pupae of *H. hebetor* could not develop into adults at −5, 0, and 5 °C, but they did develop into adults after 50 d of cold storage at 10 and 15 °C.

Table 1. The developmental stage changes in initial *H. hebetor* eggs, larvae, and pupae after cold storage at −5, 0, 5, 10, and 15 °C for 10, 20, 30, 40, 50, and 60 d, respectively.

Initial Life Stage	Temperature (°C)	Life Stage After Cold Storage for Different Durations (d)					
		10	**20**	**30**	**40**	**50**	**60**
Egg	−5	Egg	Egg	Egg	Egg	Egg	Egg
	0	Egg	Egg	Egg	Egg	Egg	Egg
	5	Egg	Egg	Egg	Egg	Egg	Egg
	10	Egg	Egg	Egg	Egg	Egg	Egg
	15	Larva	Larva	Larva	Larva	Pupa	Pupa

Table 1. *Cont.*

Initial Life Stage	Temperature (°C)	Life Stage After Cold Storage for Different Durations (d)					
		10	**20**	**30**	**40**	**50**	**60**
Larva	−5	Larva	Larva	Larva	Larva	Larva	Larva
	0	Larva	Larva	Larva	Larva	Larva	Larva
	5	Larva	Larva	Larva	Larva	Larva	Larva
	10	Larva	Larva, Pupa	Larva, Pupa	Pupa	Pupa	Pupa
	15	Pupa	Pupa	Pupa	Pupa	Pupa	Pupa, Adult
Pupa	−5	Pupa	Pupa	Pupa	Pupa	Pupa	Pupa
	0	Pupa	Pupa	Pupa	Pupa	Pupa	Pupa
	5	Pupa	Pupa	Pupa	Pupa	Pupa	Pupa
	10	Pupa	Pupa	Pupa	Pupa	Pupa, Adult	Adult
	15	Pupa	Pupa	Pupa	Pupa	Adult	Adult

3.2. Impacts of Different Low-Temperature Exposure Durations on Survival of Different Life Stages of H. hebetor

The survival rate of *H. hebetor* significantly decreased with increasing cold storage durations (df = 5, 240; F = 0.65; $p < 0.01$; Table 2). The eggs, larvae, pupae, and adults of *H. hebetor* died when stored at −5 and 0 °C for more than 10 d. Moreover, the eggs of *H. hebetor* also died after of 10 d of exposure at 5 and 10 °C. Female adults of *H. hebetor* could not survive after of 10 d of cold storage at 5 °C. The maximum survival rates of *H. hebetor* were 18.33% (exposure at 15 °C for 10 d for eggs), 32.50% (exposure at 15 °C for 10 d for larvae), 48.33% (exposure at 15 °C for 10 d for pupae), 92.50% (exposure at 15 °C for 20 d for female), and 34.17% (exposure at 5 °C for 10 d for male).

Table 2. Survival rate (%) of eggs, larvae, pupae, and adults of *H. hebetor* after cold storage at −5, 0, 5, 10, and 15 °C for 10, 20, 30, 40, 50, and 60 d, respectively.

Initial Life Stage	Temperature (°C)	Cold Storage Duration (d)					
		10	**20**	**30**	**40**	**50**	**60**
Egg	−5	0	0	0	0	0	0
	0	0	0	0	0	0	0
	5	0	0	0	0	0	0
	10	0	0	0	0	0	0
	15	18.33 ± 3.47 eA	9.17 ± 1.60 eB	5.00 ± 0.97 cBC	2.50 ± 1.60 cC	2.50 ± 1.60 cC	0
Larva	−5	0	0	0	0	0	0
	0	0	0	0	0	0	0
	5	8.33 ± 2.15 fA	5.00 ± 2.15 eA	0	0	0	0
	10	26.67 ± 4.91 dA	34.17 ± 4.17 cA	9.17 ± 0.83 cB	0	0	0
	15	32.50 ± 4.38 cdeA	28.33 ± 2.15 cA	25.00 ± 8.44 aAB	11.67 ± 2.15 bB	10.83 ± 3.70 bBC	9.17 ± 5.67 aC
Pupa	−5	0	0	0	0	0	0
	0	0	0	0	0	0	0
	5	10.00 ± 4.91 fA	5.00 ± 2.15 eB	0	0	0	0
	10	26.67 ± 4.082 dA	19.17 ± 1.60 dA	20.00 ± 4.08 bA	8.33 ± 2.15 bcB	8.33 ± 0.96 bB	0
	15	48.33 ± 7.76 bcA	47.50 ± 7.38 bA	27.50 ± 5.83 aB	18.33 ± 2.15 aB	17.50 ± 5.34 aB	13.33 ± 3.04 aB
Adult female	−5	0	0	0	0	0	0
	0	0	0	0	0	0	0
	5	36.67 ± 8.71 cdA	0	0	0	0	0
	10	58.33 ± 5.85 bA	45.83 ± 5.83 bB	0	0	0	0
	15	90.00 ± 2.36 aA	92.50 ± 3.44 aA	20.00 ± 12.25 bB	0	0	0
Adult male	−5	0	0	0	0	0	0
	0	0	0	0	0	0	0
	5	34.17 ± 6.44 cdA	0	0	0	0	0
	10	5.83 ± 4.79 fB	21.67 ± 2.15 dA	0	0	0	0
	15	0	0	0	0	0	0
Egg	30 (Control)			83.89 ± 5.97 aA			
Larva				87.87 ± 7.74 aA			
Pupa				94.12 ± 1.92 aA			

Note: The data are the mean ± standard error. Data followed by different lowercase letters in each column, and data followed by different capital letters in each row indicate significant difference according to Tukey's test at $p < 0.05$.

3.3. Impacts of Different Low-Temperature Exposure Durations on the Parasitism Rate of H. hebetor

The parasitism rate of *H. hebetor* adults originated from initial eggs, larvae, pupae, and adults after different cold storage durations significantly decreased with increasing cold storage durations (df = 5, 240; F = 2.39; p = 0.02; Table 3). The highest parasitism rate of *H. hebetor* adults originated from initial eggs (cold storage at 15 °C for 20 d), larvae (cold storage at 15 °C for 20 d), and pupae (cold storage at 15 °C for 10 d) were 22.72%, 29.73%, and 22.20%, respectively. The highest parasitism rates of *H. hebetor* adults after cold storage at 5 °C and 10 °C for 10 d were 34.12% and 30.44%, respectively, which were not significantly different from the control (31.86%).

Table 3. The parasitism rates (%) of *H. hebetor* adults originated from initial eggs, larvae, pupae, and adults after cold storage at −5, 0, 5, 10, and 15 °C for 10, 20, 30, 40, 50, and 60 d on *E. elutella* late-instar larvae.

Initial Life Stage	Temperature (°C)	Cold Storage Duration (d)					
		10	20	30	40	50	60
Egg	−5	0	0	0	0	0	0
	0	0	0	0	0	0	0
	5	0	0	0	0	0	0
	10	0	0	0	0	0	0
	15	20.21 ± 0.67 cA	22.72 ± 1.67 abA	13.54 ± 1.26 bB	0	0	0
Larva	−5	0	0	0	0	0	0
	0	0	0	0	0	0	0
	5	12.59 ± 1.165 dA	8.00 ± 0.33 cB	0	0	0	0
	10	27.7 ± 1.89 bA	21.65 ± 0.40 abA	3.33 ± 0.71 dB	0	0	0
	15	29.11 ± 1.21 aA	29.73 ± 1.24 aA	5.49 ± 1.02 cB	0.67 ± 0.33 aC	0	0
Pupa	−5	0	0	0	0	0	0
	0	0	0	0	0	0	0
	5	4.59 ± 0.32 eA	0.78 ± 0.40 dB	1.00 ± 0.58 dB	0	0	0
	10	18.17 ± 1.79 cA	16.05 ± 0.48 bA	7.27 ± 1.28 cB	0	0.33 ± 0.33 aC	0
	15	22.20 ± 4.22 cA	17.02 ± 6.37 bA	18.74 ± 1.40 aA	0	0	0
Adult	−5	0	0	0	0	0	0
	0	0	0	0	0	0	0
	5	34.12 ± 0.16 a	0	0	0	0	0
	10	30.44 ± 0.46 aA	22.93 ± 0.67 abB	0	0	0	0
	15	27.43 ± 1.02 bA	26.04 ± 1.76 aA	18.34 ± 1.56 aB	0	0	0
Adult	30 (Control)			31.86 aA			

Note: The data are the mean ± standard error. Data followed by different lowercase letters in each column, and data followed by different capital letters in each row indicate significant difference according to Tukey's test at $p < 0.05$.

3.4. Impacts of Different Low-Temperature Exposure Durations on Egg Production of H. hebetor

The fecundity of *H. hebetor* adults originated from initial eggs, larvae, pupae, and adults after different cold storage durations significantly decreased with increasing cold storage duration (df = 5, 240; F = 1.08; $p < 0.01$). The egg production of *H. hebetor* adults developed from initial eggs reached its maximum level (195.67 eggs/female) at 15 °C for 20 d exposure (Table 4). Also, the maximum level of egg production of *H. hebetor* adults developed from initial larvae exposed at 15 °C for 10 d and 20 d were 344.67 and 340.67 eggs/female, respectively, which were not significantly different from the control (392.00 eggs/female).

Table 4. The number of eggs laid by *H. hebetor* adults originated from initial eggs, larvae, pupae, and adults after cold storage at −5, 0, 5, 10, and 15 °C for 10, 20, 30, 40, 50, and 60 d.

Initial Life Stage	Temperature (°C)	Cold Storage Duration (d)					
		10	20	30	40	50	60
Egg	−5	0	0	0	0	0	0
	0	0	0	0	0	0	0
	5	0	0	0	0	0	0
	10	0	0	0	0	0	0
	15	157.00 ± 6.08 dA	195.67 ± 17.65 cA	91.33 ± 12.77 bB	0	0	0

Table 4. *Cont.*

Initial Life Stage	Temperature (°C)	Cold Storage Duration (d)					
		10	**20**	**30**	**40**	**50**	**60**
Larva	−5	0	0	0	0	0	0
	0	0	0	0	0	0	0
	5	53.67 ± 10.27 fA	31.33 ± 7.69 fB	0	0	0	0
	10	185.00 ± 9.29 cA	89.67 ± 15.19 eB	13.33 ± 3.76 cC	0	0	0
	15	344.67 ± 6.23 bA	340.67 ± 6.23 aA	5.00 ± 1.00 dB	0	0	0
Pupa	−5	0	0	0	0	0	0
	0	0	0	0	0	0	0
	5	37.33 ± 1.45 gA	0.67 ± 0.33 gB	1.00 ± 0.58 dB	0	0	0
	10	193.33 ± 33.18 cdB	262.67 ± 28.26 bA	1.67 ± 0.88 dC	0	0	0
	15	228.67 ± 57.18 cA	104.00 ± 52.03 dB	189.00 ± 21.73 aA	0	0	0
Adult	−5	0	0	0	0	0	0
	0	0	0	0	0	0	0
	5	112.00 ± 9.54 e	0	0	0	0	0
	10	430.67 ± 29.17 aA	269.33 ± 14.53 bB	0	0	0	0
	15	325.67 ± 10.9 bA	241.00 ± 21.66 bcB	82.00 ± 3.51 bC	0	0	0
Adult	30 (Control)			392.00 ± 18.25 bA			

Note: The data are the mean ± standard error. Data followed by different lowercase letters in each column, and data followed by different capital letters in each row indicate significant difference according to Tukey's test at $p < 0.05$.

3.5. Impacts of Different Low-Temperature Storage Durations on Oviposition Duration of H. hebetor

The oviposition duration of *H. hebetor* adults originated from initial eggs, larvae, pupae, and adults after different cold storage durations significantly decreased with increasing cold storage times (df = 5, 240; F = 7.71; $p < 0.01$; Table 5). When the eggs of *H. hebetor* were stored at 15 °C for 10 to 50 d, the oviposition duration of newly emerged *H. hebetor* adults ranged from 4.33 d to 15.67 d. When the larvae of *H. hebetor* were stored at 15 °C for 10 to 60 d, the oviposition duration of newly emerged *H. hebetor* adults ranged from 0.83 d to 17.00 d. When the pupae of *H. hebetor* were stored at 15 °C for 10 and 60 d, the oviposition duration of newly emerged *H. hebetor* adults ranged from 1.00 d to 15.67 d. In general, the maximum oviposition duration of *H. hebetor* adults originated from eggs, larvae, and pupae after different cold storage durations were 15.67, 17.00, and 16.00 d, respectively, but there were no significant differences from the control (15.00 d).

Table 5. The oviposition duration (d) of *H. hebetor* adults originated from initial eggs, larvae, pupae, and adults after cold storage at −5, 0, 5, 10, and 15 °C for 10, 20, 30, 40, 50, and 60 d.

Initial Life Stage	Temperature (°C)	Cold Storage Duration (d)					
		10	**20**	**30**	**40**	**50**	**60**
Egg	−5	0	0	0	0	0	0
	0	0	0	0	0	0	0
	5	0	0	0	0	0	0
	10	0	0	0	0	0	0
	15	15.67 ± 0.33 bcA	14.67 ± 0.33 bA	10.67 ± 0.33 bB	6.00 ± 0.58 aC	4.33 ± 0.33 aC	0
Larva	−5	0	0	0	0	0	0
	0	0	0	0	0	0	0
	5	9.00 ± 0.00 dA	7.00 ± 0.00 cA	0	0	0	0
	10	12.67 ± 0.33 cA	8.33 ± 0.33 cB	5.00 ± 0.00 cB	0	0	0
	15	17.00 ± 0.00 bA	15.00 ± 0.00 bA	5.33 ± 0.33 cB	2.33 ± 0.33 bBC	1.33 ± 0.33 aC	0.83 ± 0.17 aC
Pupa	−5	0	0	0	0	0	0
	0	0	0	0	0	0	0
	5	11.67 ± 0.33 cA	3.67 ± 0.33 dB	2.33 ± 0.33 dB	0	0	0
	10	16.00 ± 1.00 bA	14.33 ± 0.88 bA	4.67 ± 0.33 cB	2.33 ± 0.33 bB	2.00 ± 0.58 aB	0
	15	15.67 ± 0.33 bA	7.67 ± 1.33 cC	11.33 ± 0.88 aB	2.17 ± 0.44 bD	1.67 ± 0.60 aD	1.00 ± 0.29 aD
Adult	−5	0	0	0	0	0	0
	0	0	0	0	0	0	0
	5	11.00 ± 0.00 cA	0	0	0	0	0
	10	21.00 ± 0.00 aA	18.33 ± 0.33 aA	0	0	0	0
	15	16.67 ± 0.33 bA	14.00 ± 0.00 bAB	11.00 ± 0.58 aB	0	0	0
Adult	30 (Control)			15.00 ± 0.33 bA			

Note: The data are the mean ± standard error. Data followed by different lowercase letters in each column, and data followed by different capital letters in each row indicate significant difference according to Tukey's test at $p < 0.05$.

4. Discussion

Low-temperature storage is a useful method for mass production and application of *H. hebetor* [15]. The current research results showed that the insect life stage, temperature and period of low-temperature storage had remarkable effects on *H. hebetor* development, parasitism ability and egg production. *Habrobracon hebetor* eggs, larvae, pupae, and adults should not be stored at −5, 0, and 5 °C. When stored at or below 10 °C for more than 10 d, the eggs of *H. hebetor* could not survive, which is similar to the research results of Huang (1990) [16]. The current research results showed that *H. hebetor* larvae were more suitable for cold storage than pupae. The survival rate of pupae of *H. hebetor* significantly decreased after 10 d of cold storage at 5 °C, which is similar to previous results [9,17], indicating that pupa is not the best life stage for cold storage. Meanwhile, prolonged low-temperature exposure of *H. hebetor* pupae results in increasing proportion of adult developmental abnormalities [13]. Male adults of *H. hebetor* are extremely sensitive to low temperatures, and all of them die after more than 60 d cold storage at 10 °C [18]. The cold storage time of *H. hebetor* adults should not exceed 20 d, which significantly reduce the survival rate and egg production of *H. hebetor*, which is consistent with previous research findings [10,19,20]. Increasing cold storage time negatively affects the survival rate of each life stage of *H. hebetor* at 12 °C [20]. This current study showed that all of *H. hebetor* died after 20 d of cold exposure at temperatures below 5 °C. This is different from Chen et al. (2011) [19]. They found that storing *H. hebetor* adults at 5 °C for 20 d had no any adverse effects on lifespan and fecundity. Meanwhile, the favorable cold storage condition for adult *H. hebetor* was 10 °C or higher. This is also different from Seyahooei et al. (2018) [21], who found that 5 °C was favorable for *H. hebetor* cold storage. The differences may be attributed to different strains of the parasitoid and specific experimental conditions used in different studies.

In addition, storing *H. hebetor* adults at 5 °C for 10 d had no harmful impacts on their parasitism and egg production. If the parasitoid is gradually acclimated at low temperatures, it may effectively improve their performance after cold exposure [22]. Meanwhile, the host and other nutrients were not provided for *H. hebetor* adults during the cold storage in the present study. Thus, it deserves to further investigate whether providing nutrients can improve the parasitoid's performances after low-temperature storage, as it has been already proven in the case of other studies [23,24]. Additionally, diapause is an effective technique to boost chilling adaptation ability of parasitoids [25,26]. Storing diapausing females of *H. hebetor* at 5 °C for 8 weeks can successfully maintain their performance [27]. Meanwhile, the highest parasitism rates of *H. hebetor* adults after cold storage at 5 °C and 10 °C for 10 d were 34.12% and 30.44% in this study, respectively, which were similar to the control (31.86%). The potential reasons for why the parasitism rate of *H. hebetor* adults is better but survival is worse still deserve to be further investigated.

5. Conclusions

Cold exposure significantly decreased *H. hebetor* survival and development. *H. hebetor* parasitism rate, fecundity and oviposition duration substantially decreased with increasing cold exposure duration. Mass rearing protocols should be notably mediated according to life stage at storage. In view of the overall results, the following optimum parameters were found for *H. hebetor* with regard to life stage, cold storage temperature and cold storage duration: larvae at 15 °C for 20 days. These results are in favor of the large-scale artificial breeding and application of *H. hebetor* in practice.

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Data Availability Statement: Data are available upon request.

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