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A REVIEW ON BASIC BIOLOGY AND ECOLOGY OF INVASIVE APPLE SNAILS (*Pomacea* spp.) FOR EFFECTIVE MANAGEMENT

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ABSTRACT

Alien invasive *Pomacea canaliculata* Lamarck and *Pomacea maculata* Perry were introduced into many countries of the world from South American countries either for food, aquaculture, or to manage and control weeds or schistosomiasis vector snails. Due to mismanagement in their introduced locations, these destroyed natural wetlands and agricultural crops including rice. Both *Pomacea* spp. are highly invasive and cause significant losses in aquatic macrophytes including rice, particularly direct seeded rice, in Southeast Asian countries. In general, management of *Pomacea* spp. is based on pesticides but an understanding of their distribution, biology and performance of eco-friendly management tactics can reduce their damage and dispersion. Therefore, this review focused on the basic aspects of introduction, biology, damage and management of invasive *Pomacea* spp. for better understanding by researchers, growers and policy makers to restrict its spread.

Key words: Pomacea, invasive, botanical traps, management, snail, rice, water

INTRODUCTION

The fast economic growth during the recent past has witnessed an increasing trade and human traveling throughout the globe; thus, increased the chances of introduction of species into new areas (Blumenthal 2006). Whether an introduced species will become invasive and establish in introduced areas depend not only upon the characteristics of the introduced locality, such as species diversity in the ecosystem, availability of resources and frequency and scale of disturbances (Davis et al. 2000), but also the biology of the introduced species i.e., its feeding flexibility, reproductive potential, rate of growth and tolerance to harsh environmental conditions (Kolar et al. 2001).

Apple snails, *Pomacea canaliculata* and *P. maculata* (junior synonym *P. insularum*), originated from South America are widely distributed invasive species in the world (Cowie 2002; Hayes et al. 2009, 2015). They have high reproductive potential, fast growth rate, high dietary flexibility and strong resistance to several environmental conditions including hypoxia, high temperature and desiccation (Cowie 2002; Estebenet and Martin 2002). Thus, it has become successful invaders of rice and other macrophytes, along with natural wetlands in their introduced locations. Although, *Pomacea* spp. are invading vast wetlands in the world, a comprehensive review on basic eco-biological aspects of these snails is limited, except for de Brito and Joshi (2016), Burks et al. (2017), Horgan (2018) and Martín et al. (2019), that focused on various aspects of *P. canaliculata* and *P. maculata*, separately or restricted to specific geographical regions. Moreover, available literature has focused mainly on *P. canaliculata* than *P. maculata*, mainly because of their taxonomic confusion or earlier was spread widely in the world. However, most of the available information regarded both species as equally damaging and invasive (Martín et al. 2019). Therefore, a brief and basic information regarding various eco-biological aspects of these invasive apple snails could provide a great help to achieve challenging task of restricting their spread by adopting appropriate management strategies.

CLASSIFICATION, ORIGIN AND DISTRIBUTION

Apple snails of the class Gastropoda (Order: Architaenioglossa) belong to the family of freshwater apple snails, Ampullariidae that originated from Gondwanan in Africa. These are distributed mainly in humid tropical and subtropical habitats in Africa, South and Central America and Asia (Hayes et al. 2009). In Ampullariids, two major genera are *Pomacea* containing around 50 valid species and *Pila* with around 30 valid species. Three sub-genera, *Pomacea* (*Pomacea*) Perry 1610, *Pomacea (Effusa)* Jousseaume, 1889 and *Pomacea* (*Limnopomus*) Dell 1904 are recognized for genus *Pomacea* (Hayes et al. 2009, 2015). Although, members of the genus *Pomacea* are often referred as "*canaliculata* complex or group", but the name that attracted the world's attention is "Golden Apple snails or GAS" because of either their bright orange-yellow or financial opportunity they provided at their introduction in Southeast Asia (Cowie et al. 2006; Hayes et al. 2008). The apple snails (*Pomacea* spp.) are native to freshwater habitats of South and Central America, whereas, only one species belongs to North America (Rawlings et al. 2007). Among the invasive species, the native range of *P. canaliculata* is suggested as the natural range extended within South America (Cazzaniga 2006; Cowie 2002). However, currently it is more restricted to the Lower Paraná, Uruguay and La Plata basins, but, due to habitat similarity and connectivity of water channels, there are chances that it may also be present in the lower reaches of the Upper Paraná and parts of southern Brazil (Cowie et al. 2017; Martín et al. 2017).

During the 1980's, at least three *Pomacea* spp. i.e., *P. canaliculata, P. maculata* (junior synonym *P. insularum*) and *P. scalaris* were introduced to Asian countries, particularly Southeast Asia (Hayes et al. 2008; Lv et al. 2013). These were introduced either for food, aquaculture, or to manage and control weeds or schistosomiasis vector snails (Cowie and Hayes 2012). As snails failed to capture the market, people discarded these in the wild, where snails increased their populations and became serious pests of many aquatic flora and macrophytes including rice and taro (Cowie et al. 2017; Horgan et al. 2014a). At present, freshwater apple snails are found in many countries including Australia, Cambodia, Chile, China, Dominican Republic, Ecuador, Egypt, Europe, Guam, Indonesia, Israel, Japan, Laos, Malaysia, Myanmar, Pakistan, Papua New Guinea, Philippines, Puerto Rico, Russia, Singapore, South Africa, South Korea, Taiwan, Thailand, Vietnam, USA and some Pacific islands, notably the Hawaiian Islands (Baloch 2017; Burks et al. 2017; EFSA 2012; Ip et al. 2017; Khin et al. 2017; Ng et al. 2017; Rodriguez et al. 2017; Yahaya et al. 2017; Yang et al. 2018a). In Southeast Asia, *P. canaliculata* was thought to be the only introduced species, but later investigations confirmed the presence of other species including *P. gigas* (Spix 1827), *P. cuprina* (Reeve 1856), *P. lineate* (Spix 1827), *P. maculata* (d'Orbigny 1835) (Cazzaniga 2006; Rawlings et al. 2007). Most of the above species are misidentification of either *P. canaliculata* or *P. maculata*, the two species now recognized as well established in the Southeast Asian countries (Hayes et al. 2012). The presence of hybrid individuals of *P. canaliculata* and *P. maculata* have also been reported not only in Japan but in their native habitats of South America (Hayes et al. 2012; Matsukura et al. 2013).

MORPHOLOGY AND ANATOMY

Recent genetic studies that also include morphological characteristics of *P. canaliculata* and *P. maculata* described some distinguishable characters that could be helpful in proper identification of the two species (Table 1) (Hayes et al. 2012; Lv et al. 2013; Marwoto and Nur 2012; Rao et al. 2018). A great variation is reported among the shells of *P. maculata* and *P. canaliculata.* The shell of *P. maculata* is globular with normal coloration of brown, black and yellowish-tan and shell length could reach 150 mm or more in size. However, *P. canaliculata* shell possesses highly variable colour bands of brown, black and yellowish-tan, albino and gold colour with size could reach up to 150 mm in length. A spiral band is generally eroded in *P. maculata* with perforated umbilicus, whereas, *P. canaliculata* have highly pointed, dark spiral band with relatively large and deep umbilicus. Among the other main features, *P. maculata* possesses shallow channelled sutures, angulated body whorl and a highly pigmented (yellow, orange or red) inner lip, whereas, deep channelled suture, rounded body whorl along with not-pigmented inner pallial lip are characteristics of *P. canaliculata* (Table 1; Fig. 1 and 2). However, considering the interspecific overlap and intraspecific variability between the two *Pomacea* spp., it has been suggested that morphological characters of shell alone are not reliable for species identification. Therefore, molecular identification is required for the two most confusing *Pomacea* spp. to understand their ecological niches for the better management (Rao et al. 2018).

Table 1. Main distinguishable characteristics of *P. maculata* and *P. canaliculata*

	P. maculata	***P. canaliculata***
Shell color	Brown, become darker at Umbilicus.	Yellowish or dark brown, yellowish around suture.
Spiral band	Low and commonly eroded	High, pointed, dark, brighter at body whorl
Umbilicus	Perforate	Large and deep
Suture	Shallow channelled	Deep channelled
Body whorl shoulder	Angulated	Rounded
Inner pallial lip	Pigmented yellow–orange–red	Not-pigmented

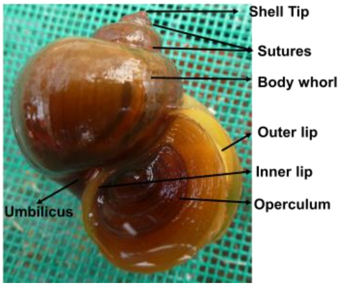

Fig. 1. Main features of a typical apple snail shell

Fig. 2. Specimen of *P. canaliculata* (left) and *P. maculata* (right) collected from the rice fields in Peninsular Malaysia (Photo by Gilal)

Respiration**:** *Pomacea* spp. possesses a dual system for gaseous exchange so that it can survive either in or outside water (Seuffert and Martín 2010). Snails can respire either through lungs or gills (ctenedium), separately or simultaneously, thus, are highly amphibious. However, the frequency of aerial respiration sharply decreased with increased temperature (Ramakrishnan 2007). Moreover, snails' have the ability to withstand harsh environmental conditions of dryness and coldness by aestivating or hibernating in the soil for a period beyond 6 months depending upon the temperature (Cowie 2002; Yoshida et al. 2009; Yusa et al. 2006a).

FEEDING HABITS AND INVASIVENESS OF APPLE SNAILS

Pomacea spp. possesses a wide variety of feeding habits mainly due to its horny radula and includes microphagous, zoophagous, macro phytophagous and detritovores but, none being mutually exclusive (Cowie 2002; Estebenet and Martín 2002). During its initial development, *Pomacea* spp. normally feed on algae or other soft bodied detritus materials, but with growth, feeding shifts towards higher plants such as rice (Arfan et al. 2015b).

Damage to rice and other macrophytes. *Pomacea canaliculata* and *P. maculata* are reported to cause significant losses to rice in many Southeast Asian countries including Taiwan, Japan, Philippines, Thailand, Malaysia, Indonesia, China and Vietnam (Arfan et al. 2014; Burlakova et al. 2009; Suharto et al. 2006). They also feed on a wide variety of macrophytes of varying importance including taro, swamp cabbage, lotus, mat rush, Chinese mat grass, wild rice, Japanese parsley, water spinach, water chestnuts, azolla, maize and citrus (Burks et al. 2011; Burlakova et al. 2009).

Damage by apple snails to rice is observed by missing hills and floating rice fragments in the field (Fig. 3) (Arfan et al. 2016a; Sanico et al. 2002). However, damage to rice is mostly dependent on the size and density of the snails and stage of the rice crop (Arfan et al. 2016b; EFSA 2012). The snail density of 1 snail / m^2 and 8 snails /m^2 could reduce the rice yield up to 20%, and 90%, respectively (Arfan et al. 2016b; Naylor, 1996). The snails with shell height of > 5 cm can cause three times more damage than snails with shell height < 2 cm, whereas, snails less than 5 mm mostly feed on algae and other detritus materials in the field (Naylor 1996; Arfan et al. 2015b). Sowing methods and stage of rice crop also affect the amount of damage caused by *Pomacea* spp. as they cause severe damage to direct seeded rice up to 4 weeks and young transplanted (21 and 28 days) rice seedlings up to 2-3 weeks (Arfan et al. 2016b; Lee et al. 2010; Sanico et al. 2002). No damage by *Pomacea* spp. has been observed after 5th week of transplanting in 21 and 28 days old transplanted seedlings (Arfan et al. 2016b; Horgan et al. 2014b; Sanico et al. 2002).

Fig. 3. Missing patches in a Malaysian rice field due to feeding of *Pomacea* spp. (Photo by Gilal)

Irrigation water in the field also contributes significantly to rice damage by the apple snails, as water level above the shell height of snails increase their mobility and thus, damage (Arfan et al. 2016b; Liang et al. 2013; Sanico et al. 2002; Teo 2003). Significant reduction in the loss of rice grown by direct and 21 days transplanted seedlings was also recorded when water was drained out to saturated level after sowing (Arfan et al. 2016b; Teo 2003). Comparatively higher loss of rice seedlings (up to 90%) can be attributed to higher densities in comparison to 20% loss at 1 snail / m^2 density (Arfan et al. 2016b; Lee et al. 2010). It is also reported that one adult snail is capable of consuming around 24 young seedlings per day (Cowie 2002). Among the factors responsible for the damage of *Pomacea* spp. to rice, role of water level is more significant than stage of rice crop and snail density (Teo 2003).

Threat to natural ecosystems. Although, most of the studies on *Pomacea* spp. focused on their importance as pests of rice, but their effects on the natural wetlands are also enormous as they disturb the normal ecosystem functions (Horgan et al. 2014a; Nghiem et al. 2013). Higher populations of *P. canaliculata* have caused complete destruction of aquatic plants, thus, resulting in higher phytoplankton densities and turbid waters (Carlsson 2017). Thus, shift of clear and aquatic rich wetlands to turbidity because of *Pomacea* spp., has disturbed their normal functionality to provide food, fodder and habitats to many aquatic organisms (Carlsson 2017). In North America, it has been observed that differential feeding of the *P. maculata* has also facilitate the growth and dispersal another invasive macrophytes species, *Hydrilla verticillata* in to takeover native macrophytes (Meza-Lopez and Siemann 2015; Monette et al. 2017).

Vectors of diseases. *Pomacea* spp. are also vectors of many hazardous diseases of human beings (Table 3). Angiostrongyliasis is caused by the two parasitic nematodes i.e., *Angiostrongylus cantonensis* (causal organism of fatal eosinophilic meningitis and meningoencephalitis) and *A. costaricensis* (that cause causal organism of abdominal angiostrongyliasis, a gastrointestinal syndrome) in human beings and other mammals including birds in many tropical and subtropical countries (Murphy and Johnson 2013). These diseases are mostly transferred to humans through consumption of gastropod snails including *P. canaliculata* that act as its intermediate host (Kim et al. 2014) and the same was evident during the outbreaks of eosinophilic meningitis in China (Yang et al. 2013) and other regions of the world (Kim et al. 2014; Kwon et al. 2013; Thiengo et al. 2013). *Pomacea* spp. are also reported as vectors of schistosomiasis caused by schistosomiasis worms that cause infection in the urinary tract or intestine (Cantanhede et al. 2014). Gnathostomiasis is an unusual human infection of intermittent subcutaneous swellings and (often) intestinal nodules, and an inflammatory reaction associated with production of many eosinophils. *Gnathostoma spinigerum*, the casual organism of Gnathostomiasis, enters the human body through consumption of raw *P. canaliculata* and *Pila ampullacea* (Komalamisra et al. 2009).

Table 3. Global distribution of diseases spread by *Pomacea* spp. as vectors

Disease	Casual organism	Countries
Angiostrongyliasis	*Angiostrongylus cantonensis* *A. costaricensis*	Thailand, Brazil, China, USA, Cuba, Ecuador, Japan, Australia, India, Vietnam, Malaysia, Egypt, Sri Lanka, Cambodia, Samoa, Fiji, Belgium, Costa Rica, Germany, Indonesia, New Zealand, Papa New Guinea, UK.
Schistosomiasis	*Schistosoma* spp.	Much of Sub-Saharan Countries (especially Somalia, Sudan and Yemen, Egypt), Brazil, Surinam, Venezuela, The Caribbean, Arabic Peninsula, Indonesia, Philippines, Laos, Cambodia.
Gnathostomiasis	*Gnathostoma spinigerum*	Thailand, Japan, India, Vietnam, Myanmar, Lao PDR, Cambodia, China, Bangladesh, Malaysia, Indonesia, Philippines, Palestine, Israel, Australia, USA, Mexico, Ecuador

(Doumenge and Mott 1984; Kliks and Palumbo 1992; Alto 2001; Lindo et al. 2002; Cowie 2013; Gryseels et al. 2006; Komalamisra et al. 2009; Maldonado Jr. et al. 2012).

***Threat to other invertebrates*.** The higher populations of invasive *Pomacea* spp. have also adversely affected the population of other benthic individuals such as worms, crustaceans and snails, especially in the absence of macrophytes, algae or detritus matter (Horgan et al. 2014a; Kwong et al. 2009). In Thailand, increasing density of *P. canaliculata* had adversely affected the populations of the native *Pila scutata* due to its higher growth, indiscriminate feeding and higher food consumption (Chaichana and Sumpan 2014). In USA, *P. maculata* showed severe effects on the growth and development of native *P. palusoda* (Posch et al. 2013). The ability of the invasive *Pomacea* spp. to consume fresh and partially rotten materials of various invertebrates and invertebrates (Saveanu et al. 2017; Aditya and Raut 2001) competed severely with other macro-invertebrate detritivores, particularly insects which are not so specialized in comparison to *Pomacea* spp. (Fenoglio et al. 2014).

***Quantitative losses due to apple snails*.** Little information is available on the quantitative yield-loss assessments and the most comprehensive study was that of Naylor (1996). Estimated monetary losses caused by the *P. canaliculata* in Philippines, Thailand and Vietnam were between \$806 to \$2,138 million at a snail density of more than 1 snail / m^2. However, the actual losses in the entire Southeast Asian countries including Malaysia and Indonesia may be even higher because the above-mentioned figure did not include the health and environmental losses caused by *P. canaliculata* (Naylor 1996; Ngheim et al. 2013). Due to significant adverse effects of apple snails on the cultivated crops, managed wetlands and as vectors of human diseases, one of the species, *P. canaliculata* has been included in the world’s 100 most invasive species (Lowe et al. 2000).

LIFE CYCLE AND REPRODUCTION

Freshwater snails are gonochoristic and oviparous with internal fertilization (Wu et al. 2011). *Pomacea* spp. show sexual dimorphism where females are relatively larger and heavier. Females possess more oval aperture that curves into the shell i.e., concave; whereas, males possess convex operculum (curves away from shell) (Estebenet et al. 2006; Gamarra-Luques et al. 2013; Wu et al. 2011). The life stages of the pomacean snails consist of eggs with hatching period of 7-14 days, juvenile period of 14-21 days, whereas, they become fully mature in 60-80 days (Arfan et al. 2015a; dela Cruz et al. 2001; Liu et al. 2012). The snails can live up to two years in rice fields with life span of up to 4 years is reported for *P. canaliculata* (Estebenet and Martín 2002). *Pomacea* spp. possessed two types of breeding cycles depending upon the environmental factors, especially temperature. They are either semelparous (with one breeding cycle during the entire life) under tropical conditions or iteroparous (with more than one breeding cycle during the entire life) under temperate conditions. The life cycle of *P. canaliculata* varies from 3-6 years in temperate regions, whereas much shorter in tropical habitats (around one year) (Estebenet and Martín 2002).

In both *Pomacea* spp., mating took place mostly at night or early morning in water, however, mating may be continued for several hours and snails can mate repeatedly; about three times per week (Estebenet and Martín 2002; Arfan et al. 2015a). During mating, males remained firmly attached to female’s last shell whorl using their foot and remained without feeding during the entire course of mating. Prolonged copulation in *Pomacea* spp. is naturally required to transfer enough sperms to fertilize thousands of eggs produced by females. No effect of male size, timing to start copulation, mating status and presence of prowler males was determined on the duration of copulation (Burela and Martín 2009).

Fecundity. In *Pomacea* spp., oviposition usually occurs after 24 hours of copulation and continued up to 2 weeks; however, females could store sperms up to 140 days. *Pomacea* spp. always oviposit brightly colored eggs (Fig. 4) on raised surfaces mainly at night or early mornings to lower the risk of predation and desiccation (Estebenet and Martín 2002). Several studies on comparative features of oviposition in *P. maculata* and *P. canaliculata* reported comparatively large number of smaller eggs in *P. maculata* than *P. canaliculata*, that oviposit fewer number of large eggs (Arfan et al. 2015a, b; Barnes et al. 2008; Hayes et al. 2012; Kyle et al. 2013). A high variation in total number of eggs is also reported as eggs are laid in clutches of varying sizes and a snail can lay up to 4751 eggs per clutch (Barnes et al. 2008; Estebenet and Martín, 2002). Moreover, average number of eggs in *P. maculata* and *P. canaliculata* are reported as 1500 and 260, respectively (Hayes et al. 2012). The variation in fecundity may be due to the age and size of females, food, population density and environmental conditions as older females produced less egg clutches with fewer eggs (Estoy et al. 2002a, b; Tamburi and Martín 2011) (Table 2).

Fig. 4. Egg masses of *P. canaliculata* (left) and *P. maculata* (right) (Photo by Gilal)

Fertility. A great variation in mean hatching success of *P. maculata* and *P. canaliculata* can range between 0% to 100% (Arfan et al. 2015a, b; Barnes et al. 2008; Liu et al. 2012). Moreover, a highly significant difference is also observed in the hatching success of *Pomacea* eggs under field and laboratory conditions as fertility percentage of 70% and 30%, respectively was observed (Barnes et al. 2008). A huge variation in the hatching period of *Pomacea* spp. eggs ranged from 8 to 20.7 days (Arfan et al. 2015a, b; Liu et al. 2012) (Table 2). The differences in hatching success and period is mostly depended on the temperature and other environmental factors (Barnes et al. 2008).

Table 2. Main biological parameters of *P. maculata* and *P. canaliculata*

	P. maculata	***P. canaliculata***
Average eggs / clutch	1500	260
Egg diameter (mm)	2.00	3.00
Length of egg clutch (mm)	27.0-30.3	42.3-58.4
Width of egg clutch (mm)	14.67-17.6	18.6-22.9
Mean hatchling width (mm)	1.192	2.598
Mean hatchling length (mm)	1.249	2.754
Mean hatching %	73.1	69.9
Mean hatching period (days)	12.7	13.2

(Barnes et al. 2008; Liu et al. 2011; Hayes et al. 2012; Arfan et al. 2015a)

EFFECT OF ENVIRONMENTAL FACTORS ON LIFE HISTORY TRAITS OF APPLE SNAILS

Temperature is known to have significant effect on all the biological activities of apple snails, *Pomacea* spp. (Seuffert et al. 2010; Wada and Matsukura, 2017). Increased activities of *P. canaliculata* with increasing temperature from 20ºC to 32ºC are reported as snails become more active during night than day (Hieler et al. 2008). Moreover, it is also observed that activity of snails tended to decrease above the temperature of 32ºC (Seuffert et al. 2010; Seuffert and Martin 2013). Two distinct temperature regimes have been reported for the individuals of *P. canaliculata*. The lower temperatures of 15°C and 20°C, where snails showed very minimal growth with no mortality and, the higher temperature regimes of 25°C, 30°C and 35°C that showed higher snail growth at the expense of survivalability as temperature increased. The optimum temperature suggested for higher populations of *P. canaliculata* is 25ºC to 30ºC (Seuffert and Martin 2013, 2017). Moreover, it has also been suggested that the lowest and prolonged temperatures during the coldest months could restrict the spread of *P. canaliculata* into new areas (Lei et al. 2017; Yoshida et al. 2009). Both species are also found resistant to variable drought conditions with females comparatively less susceptible than males (Glasheen et al. 2017).

Pomacea spp. can also survive pH and salinity ranging 4.0 to 10.5 and 0-6.6%, respectively. Survivability of *P. maculata* at relativity humidity range of 75% to 95% was also recorded (Arfan et al. 2014; Ramakrishnan 2007). Moreover, pH below 5.5 had detrimental influence on the growth and survivability of snails and could be proved lethal. However, pH between 5.5 - 9.5, salinity below 16 and higher relative humidity favor the survival of both *Pomacea* spp. (Bernatis et al. 2016; Byers et al. 2013).

CONTROL MEASURES

Generally, it is almost impossible to eradicate the developed population of the alien invasive species. Therefore, it is important to deal the population of invasive snail species before their establishment at any locality (Byers et al. 2002; Carlton and Ruiz 2005). Accordingly, several cultural, mechanical and chemical control measures have been developed to reduce the population of *Pomacea* spp. below threshold levels. However, only a strategy that combines all possible control measures may be effective in controlling the pomacean snails. But, so far, no combination is proved quite effective and their effect on the crop yield are also unknown (Byers et al. 2002).

Cultural and mechanical control

Sowing methods**:** Alteration in time of sowing has proved to be effective in reduction of snail damage to rice as comparatively more damage is recorded in direct seeded and 2 weeks old seedlings than 4 to 6 weeks old seedlings (Sanico et al. 2002; Teo 2003). In comparison to complete loss caused to direct seeded and 14 days old transplanted rice, no more loss is reported in 21 and 28 days old seedlings after week five of transplanting (Arfan et al. 2016b). Moreover, combination of increasing the number of seedlings per hill and hand picking has effective in reducing the snail damage (Sanico et al. 2002; Yanes et al. 2014).

Water management**:** The management of irrigation water in rice field has proved the most effective method in reducing the snail's mobility and thus damage (Arfan et al. 2016b; Takashi 2004; Teo 2003). Moreover, construction of slightly deeper ditches in or around the paddy field can also facilitate the collection and destruction of snails by hand or by treating with a pesticide, because they congregate around ditches when paddy fields are fully drained out (Cowie 2002).

Botanical traps: Different kinds of traps i.e., leaves from lettuce, cassava, sweet potato, taro, tapioca, Gliricidia and papaya are tested with varied success for the attraction, collection and killing of *Pomacea* species (Cowie 2002; Lee et al. 2010). Studies in Malaysia showed potential of jackfruit skin and damaged pomelo (Syamsul et al. 2016) along with papaya (Badrulhadza and Hafizi 2014) to attract higher numbers of both adult and juvenile snails; hence, help in their collection and destruction.

Crop rotation**:** Crop rotation has also proved effective in reducing the population of *P. canaliculata* when rice was planted with soybean in rotation (Wada et al. 2004).

Picking and destruction of eggs and snails**:** Hand picking of snails and their eggs, although time consuming and labor intensive, is the most effective non-chemical method to reduce their population in the field (Kunimoto and Nishikawa 2008; Suharto et al. 2006). Collection of eggs can also be improved by placing the sticks in the field for oviposition of females (Cowie 2002).

Construction of wire-mesh grills: Construction of wire-mesh grills at the rice inlets also restrict the snail's entry to rice field as snails can easily be collected and destroyed at these grills (Teo 2003).

Water spray on eggs**:** It is reported that water spraying and submersion of *Pomacea* spp. eggs could reduce the hatching rate up to 5.8% and increase the hatching period up to 26.4 days. However, timing and frequency of water spraying is crucial as maximum results were obtained when submersion could start 6 hours after egg laying and continued for 48 hours (Wang et al. 2012). However, Ostrom and Chesnes (2014) found no significant role of submersion of eggs to control *P. maculata*, instead, suggested that submersion may facilitate their distribution to new areas.

Biological control: A comprehensive review of de Brito and Joshi (2016) highlighted the role of natural enemies against *P. canaliculata*, but, in their native habitats, none of the natural enemies showed significant result in regulation of *Pomacea* spp. population. However different predators, such as fishes, birds, rats, lizards, ants, amphibians and insects have been evaluated with varying degree of success in different courtiers (Dong et al. 2012; Halwart 1994a; Yusa 2001). Forty-six predator species from 16 orders have been tested in various countries against different stages of *Pomacea* spp., especially juveniles and showed variable success in controlling snail populations (Yusa et al. 2006b). Among natural enemies, ants i.e., *Solenopsis geminate* and *Pheidologeton* spp. can be a potential predators of eggs of *P. canaliculata* as 50% predation was recorded in Philippines (Yusa et al. 2006b; Yusa, 2001). Ducks are most widely and successfully used predators of to restrict the population of adults and juveniles released at a population of 5 to 10 ducks / hectare for one month. Ducks are released in the field prior to planting and 35-40 days after the emergence of seedlings (Halwart, 1994b; Liang et al. 2013; Teo, 2001; Vega et al. 2007).

Many fish species especially black carp (*Mylopharyngodon piceus* (Richerdson), common carp (*Cyprinus carpio* Linnaeus), Nile tilapia (*Oreochromis niloticus* Linnaeus), African catfish (*Clarias gariepinus* Burchell), *Clarias batrachus, Anabas testudineus, Ompok bimaculatus* and *Osphronemus exodon,* along with the turtles *Malayemys subtrijuga, Chinemys reevesii* and *Pelodiscus sinensis,* and the freshwater crab *Esanthelphusa nimoafi* are reported to consume *Pomacean* snails (Carlsson et al. 2004; Dong et al. 2012; Teo 2006; Yeo 2004; Yoshie and Yusa 2008; Yusa 2001; Yusa et al. 2006b). However, only common carp and African catfish showed some promising results. Common carp at a density of 2041 fishes / hectare could reduce the *P. canaliculata* population significantly, but construction of a separate pond was suggested to increase the survivability and efficacy of the fish (Teo 2006). Land snail, *Quantula striata,* raccoon (*Procyon lotor*) and leech, *Whitmania pigra* have also shown promising predation on various stages of *P. canaliculata* under field and lab conditions (Carter et al. 2017; Guo et al. 2017; Ng and Tan 2011).

Among micro-organisms, two isolates i.e., CKP-012 and CKP-032 of entomopathogenic fungi, *Paecilomyces lilacinus* have showed promising results in controlling the snail eggs, whereas only CKP-012 showed mortality among newly hatched hatchlings. However, effectiveness of CKP-012 against juveniles decreased with increasing age. LC$_{50}$ of CKP-012 for preventing hatchling of one-day old was 8.63x10^7 conidia / ml for 2.26 days, whereas 1.74x10^8 conidia / ml for 3.43 days were required to kill 50% one day old hatchlings (Maketon 2009).

Chemical control

Synthetic pesticides: Despite the human and environmental concerns, use of pesticides, not specifically molluscicides, is the first choice of the growers to control the population of freshwater apple snails (Cowie 2002). Different chemicals i.e., copper sulphate, calcium cyanamide, sodium pentachlorophenolate, niclosamide; various organo-tin compounds, endosulfan, metaldehyde, cartap hydrochloride, and isazophos are used and evaluated for the control of ampullariids. Many of these chemicals have serious human and environmental hazards and are banned in many countries of the world (Halwart 1994b; Schnorbach et al. 2006). Niclosamide and metaldehyde are presently the more appropriate molluscicides as bait type application of metaldehyde could reduce the snail population in the field even during heavy rains because of its slow release of active chemicals (Schnorbach et al. 2006; Takashi 2004).

Botanical pesticides. Although research has been carried out on various botanical molluscicides (de Brito and Joshi 2016), but so far, no significant success in development of commercial botanical molluscicides has been achieved to be used against the ampullariids (Martín 2006). However, saponins and quinoa saponins are the widely studied plant chemicals against *Pomacea* spp.

Various extracts of neem¸ *Azadirachta indica* show molluscicidal activities against *P. canaliculata* that was comparable to niclosamide (Noor and Mohd 2017). A recent study also evaluated the efficacy of methanol crude extracts of *Andrographis paniculata, Entada spiralis, Ficus deltoidea, Furcraea selloa* and *Ipomoea batatas* along with niclosamide against *P. maculata* and reported that *F. selloa* and *E. spiralis* showed similar feeding deterrent potential as that of niclosamide. Moreover, *F. selloa* extracts also exhibited maximum (80%) mortality of the targeted *P. maculata* at 15 ppm (Anis et al. 2019). In addition, more recently, extracts of several plants have been exploited against various stages of *Pomacea* spp. with varying degree of success (Table 4). Despite wide scale usage of both synthetic and botanical chemicals, these are not so effective to control *Pomacea* spp., as snails can avoid pesticides by burrowing deep into the soil or move away to other vegetation through running water and later become the source of infestation. Moreover, continuous hatching of eggs being is not affected by most chemicals and can add to population build-up of snails. Moreover, molluscicides were also found to be toxic against the developing rice seedlings (Joshi et al. 2005).

Table 4. Various botanical pesticides used against *Pomacea* spp. (continuation of de Brito and Joshi 2016)

Botanical Name	Active compound(s)	Effective Concentration	Reference(s)
Azadirachta Indica	Azadirachtin	1.97 g/L^{-1} (juveniles) 2.51 g/L^{-1} (adults)	Harun et al. 2016
Pueraria peduncularis	Pedunsaponin A Pedunsaponin C	5.511 mg L^{-1}	Yang et al. 2017
Cymbopogon citratus	α & β- citral	Not available	Ibrahim et al. 2017
Piper bitle	eugenol	Not-available	
Curcuma longa	terpenes	32.475 g L^{-1}	Mansur et al. 2018

Botanical Name	Active compound(s)	Effective Concentration	Reference(s)
Cymbopogon citratus		30.503 g L^{-1}	
Solidago canadensis	esters, alcohols	1.49 g L^{-1}	Shen et al. 2018
Schima superba	pentacyclic triterpenoid saponins	8.33 mg L^{-1}	Yang et al. 2018b
Carica papaya *Artocarpus integer*	flavonoids, saponins	18. 5 g/L^{-1} 39.8 g/L^{-1}	Latip et al. 2018
Chenopodium quinoa	saponins	Not-available	Castillo-Ruiz et al. 2018
Allium sativum	alkaloids and tannins	Not-available	Garin et al. 2019
Chimonanthus nitens	esters, alcohols, chimonanthine	Not-available	Li and Zou 2019
Ilex paraguariensis		Decoction extract (31.39 mg L$^{-1)}$; Butanol extract 24.75 mg L^{-1}	Brito et al. 2019

CONCLUSION

The invasive apple snails i.e., *P. canaliculata* and *P. maculata* has caused very serious and heavy losses to humans after their introduction to various countries of the world from their native South American origin. Multiple factors contributed towards their successful invasion to their new introduced locations. However, basic information related to their biology, feeding habits, damage, factors responsible for their spread and possible management measures discussed here could provide a comprehensive understanding of their invasiveness. Therefore, appropriate efforts should be taken not only to restrict their further spread but adopt appropriate measures especially cultural and mechanical to reduce populations of apple snails below threshold levels.

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