JOURNAL OF THE
WORLD AQUACULTURE SOCIETY

Vol. 49, No. 3
June, 2018
doi: 10.1111/jwas.12514

Factors Driving Aquaculture Technology Adoption

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Abstract

Technology adoption has played a key role in the global development and increase in agricultural productivity. However, the decision to adopt a new technology on farms is complex. While the factors that drive the adoption of new technologies have been well studied in agriculture, less attention has been paid to drivers of technology adoption in aquaculture. Aquacultural technologies have developed and advanced rapidly in recent decades, but not all technologies have been adopted readily by farmers. This review paper summarizes some of the critical factors that influence aquaculture technology adoption decisions such as: (1) method of information transfer, (2) characteristics of the technology, (3) farm characteristics, (4) economic factors, and (5) sociodemographic and institutional factors. Fish farmers have tended to adopt technologies that are perceived to be more advantageous than others in terms of productivity, cost efficiency, and ease of management. Price of aquaculture products and profit expectations from business ventures were key economic factors influencing adoption decisions. Given the wide array of species, production practices, and global nature of aquaculture, the intensity and the extent of adoption of technologies depend on the nature of the industry in which they are adopted and their economic, social, political, and regulatory environments.

KEYWORDS

aquacultural productivity, Atlantic salmon, genetically improved farmed tilapia, hybrid catfish, relative advantage, technology adoption

Adoption of new technologies developed through research and development has played a key role in the evolution of agriculture (Rauniyar and Goode 1992) and of aquaculture. However, farmers do not adopt technologies just because they exist and are available. It can be frustrating to aquaculture researchers when farmers do not adopt technologies that they have developed. The decision to adopt a new technology is complex, and the farmer must consider a wide variety of factors to determine if it is in the best interest of the farm to do so at any given point in time.

Technology adoption has been well studied in agriculture beginning with the seminal studies by Ryan and Gross (1943) and Griliches (1957). This literature reflects analyses of factors that influence decisions to adopt a new technology as well as the technology dissemination process across groups of farmers as more and more individuals choose to adopt a new technology on their farms.

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Modern technologies can aid in the growth of an aquaculture sector through (1) greater farm productivity, (2) increased fish supply and reduction in consumer prices (Asche 2008), (3) increased trade and export of fish, and (4) employment generation that benefits overall development (Dey et al. 2006). Dissemination of technologies such as artificial spawning of commercially important species, improved feeds and feeding technologies, enhanced production systems, disease management, and genetically improved fish strains were shown to have triggered aquaculture development in shrimp, salmon, and tilapia industries (Kumar and Engle 2016).

The objectives of this paper are to review both the theoretical and empirical literature related to the complex factors that may influence an aquaculture farmer's decision to adopt a new technology as well as the considerations related to the spread of new aquaculture technologies. Hence, this review is sectioned to detail the (1) factors that influence an aquaculturist to adopt a new technology and (2) process of spread of new aquaculture technologies. Improved understanding of the factors that influence adoption of technologies on farms and the dissemination of technologies across an industry may be useful for extension personnel and policy makers concerned with increasing the rate of adoption of beneficial technologies.

Factors that Influence an Aquaculturist to Adopt a New Technology

Adoption of agricultural technologies is influenced by a variety of micro- and macroeconomic factors (Feder et al. 1985). Most of the agricultural technology adoption literature highlights a few key factors that influence decisions on farms such as perceptions of the new technologies, resource utilization efficiency of technologies, economic and social policies, and infrastructural and institutional resources. These factors are not discrete or exclusive and have meager boundaries, which often overlap and have a cumulative effect on adoption decisions due to their codependency. Given their significant influence on the technology adoption process, trying to separate each characteristic from the others is challenging and may be unnecessary. This paper attempts to depict the effect of some key factors on technology adoption while letting the potential adopters to define and refine strategies given the wide array of theoretical and qualitative results. Although not exhaustive, from an aquaculture perspective, we have grouped these factors into five broad categories in no particular rank order: (1) source of information, (2) characteristics of the technology, (3) economic factors, (4) farm characteristics, and (5) sociodemographic and institutional factors. Figure 1 conceptually portrays a generalized picture of how these factors influence the technology adoption process.

Method of Information Transfer

Success of a new technology relies strongly on mechanisms of its dissemination (Rogers 1995). The effective transfer of technology (ToT) is facilitated when knowledge, information, and skills pertaining to new technologies get transferred from its source of invention to a wide range of potential end users (Brown and Ratna 2013). In what is essentially a communication process (Deutschmann and Borda 1962), knowledge gathering agencies (e.g., extension) bridge the gap between source of innovation (R&D firms) and end users (farmers). This section details some of the key approaches used by extension agents to promulgate technology transfer along with detailing their role in propagating useful technologies.

Extension Approach

Contact with extension personnel is a very important positive determinant of technology adoption (Bradfield 1966; Just and Zilberman 1983; Shields et al. 1993; Blackman 1999) as it counterbalances the negative effects arising from technology complexities (Feder et al. 1985; Joffre et al. 2017), thus promoting ToT, management practices, and knowledge (Evenson 2001). The traditional agricultural extension follows a linear approach wherein research results are extended to farms, leading to adoption and increased productivity. However, this

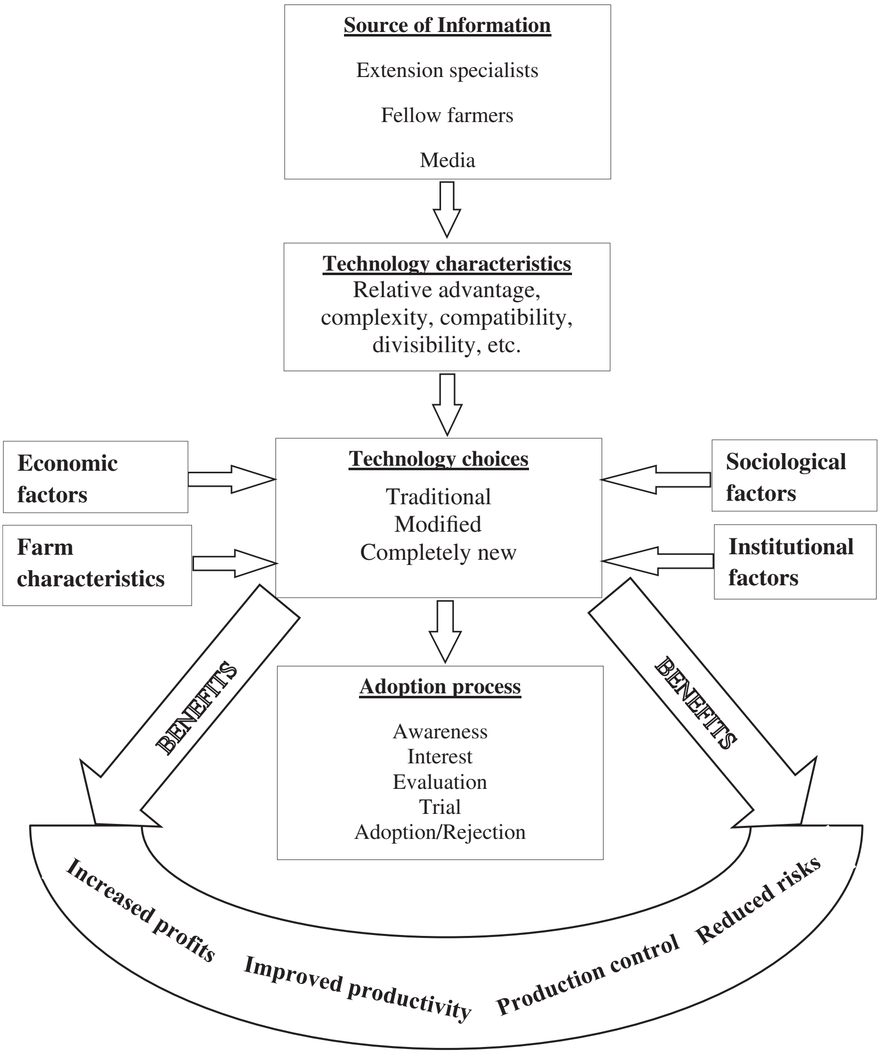

FIGURE 1. *Conceptual model for technology adoption.*

ToT approach is often met with failures due to the (1) inability in transforming research outputs into developmental impacts, (2) failure to tackle complexities associated with new technology, (3) failure to appreciate local and indigenous knowledge, and (4) lack of continuous learning about technology, environment, and the society (Lundy et al. 2007). The Farming system research approach contextualized participatory research and moved away from a one-directional teaching to a feedback-based approach, thus facilitating continual technology adoption at the farm level. However, this approach failed to incorporate the changing needs of the society into which the technologies are incorporated and retained its concentration primarily at the farm level (Edwards 1998). System approaches respond to changes in the technology environment by emphasizing interactive learning between farmers, researchers, extension, technology suppliers, and policy makers. This approach induces reversal of learning where researcher and extension workers are learning from farmers. The forward and backward interactions among stakeholders promote continuous learning by adapting to changing social, economic, ecological, and regulatory environments (Schut et al. 2015).

Some of the more successful extension technology transfer efforts are those which include producers in the program planning, development, implementation, and evaluation phases (Molnar et al. 1985; Lovshin et al. 1986). Such participatory approaches have greater likelihood of success as local priorities are also incorporated during the development of programs. Nandeesha et al. (2012) showed historical existence of the positive effects of a coordinated technology partnership among extension services and Asian fish farmers. Extension agencies were instrumental in the development and promotion of value-chain services; for example, cooperatives, warehouses, and postharvest services in developing countries often eliminated issues hindering marketing of aquaculture products. Participatory research programs, such as yield verification programs in the US catfish industry (Heikes 1997) and demonstration trials in the Asian shrimp industry (Pananond 2006), facilitated transfer of several aquaculture technologies. Participatory approaches through programs, such as Fish Farmer Field Schools (FFS), were instrumental in the improvement of aquaculture practices in several developing countries (Brown and Ratna 2013). Such aquaculture extension efforts promoted were designed at grassroot levels with better understanding of local community needs and provisions for continual support for learning.

State universities and extension services were instrumental in the development of culture, propagation, and management practices for the US catfish (Tucker et al. 2003, 2004) and baitfish (Stone et al. 2016) industries. The role of the Asian Institute of Technology (AIT), International Centre for Living Aquatic Resource Management (ICLARM, now WorldFish Center), United States Agency for International Development (USAID), and several US state universities in technology development and transfer is immense (Hatch and Tai 1997).

Extension was found to play a major role in promotion and adoption of sustainable aquaculture practices (Pemsl et al. 2006). Frequency of extension contacts was identified as a critical factor determining the adoption of fish farming in Cameroon (Wandji et al. 2012). Caffey and Kazmierczak (1994) identified extension support as a critical factor in the adoption of intensive softshell crab farming. Fish farmers who used extension help were better resource utilizers (Ahmed et al. 1995) and were found to be technically efficient and more proactive when it comes to adopting new (Dey et al. 2005; Kaliba and Engle 2006; Nguyen et al. 2017; Pemsl et al. 2006) and sustainable aquaculture practices (Murshed-E-Jahan et al. 2008). Similarly, familiarity with on-farm extension programs was found to be an important determinant in the adoption of alternate-production systems in the US catfish industry (Kumar 2015).

Media and Training

Information reduces the uncertainties associated with technology performance (Caswell and Zilberman 1986) and demystifies its complexities. Information is acquired through informal sources such as the newspaper, television, radio, scientific literature, site visits, meetings, and farmer organizations and through formal education. Exposure to information about a profitable technology induces its adoption (Rogers 1995). Although print scientific/extension literature remains an important information portal (Diekmann et al. 2009), the advent of internet and social media has made farming information ubiquitous. Chilean aquaculture producers who had greater access to internet had greater participation in organization and were willing to undertake more innovations on farms. The study by Salazar et al. (2018) also found that Internet access promotes the extent and intensity of adoption of innovation on farms. However, the ubiquitous nature of information about technology on the Internet and social media makes it all the more important that farmers receive the right mix of reliable, consistent, and accurate information about a particular technology in its proper format, time, and quantity (Joffre et al. 2017).

Training was a key variable affecting the choices of carp-farming practices in several Asian countries (Ahmed 1997). Lack of technical knowledge was identified as a significant deterrent to adoption of aquaculture technologies in Bangladesh (Pemsl et al. 2006), Malawi (Dey et al. 2006; Pemsl et al. 2006), and the USA (Kumar 2015), as well as disadoption of aquaculture technologies (Dey et al. 2006). Long-term training was found to improve the understanding about the need for better water quality and feeding management among small-scale aquaculture farms in Bangladesh (Murshed-E-Jahan et al. 2008). As in the green revolution, training methods such as the FFS were instrumental in aquaculture for propagating yield-improving technologies (Brown and Ratna 2013). Propagation of ornamental fish farming in rural areas of India was significantly improved through hands-on-training programs organized by extension activities of several central and state agencies (Silas et al. 2011). Similarly, field-school trainings were instrumental in the propagation of polyculture practices in Indonesia through provision of technical and hands-on training to local farmers (Brown and Ratna 2013). Community-based aquaculture programs in India initiated by Krishi Vigyan Kendras were instrumental in developing successful aquaculture entrepreneurship in polyculture and integrated aquaculture (Radheyshyam et al. 2013). Effective national- and regional-level training of coastal Indian farmers was instrumental in the improvement of aquaculture practices such as pearl oyster farming, mud crab, and green mussel farming (Subramnannian 2013). Training was also found to significantly influence the degree of innovativeness among small-scale aquaculture firms in Chile (Salazar et al. 2018). Regional aquaculture development agencies in several countries are increasingly using communication and information technologies to reduce the learning and information gap (El-Gayar 1997; Bostock et al. 2009). Effective training programs organized by agencies such as FAO (Engle 1988) and World-Fish Center (Murshed-E-Jahan et al. 2008) were instrumental in promulgating technologies that improved farm productivity. Extension agents are increasingly involved in the future planning of aquaculture development and planning by incorporating local farmers' knowledge into strategic planning at the onset of farming season (Joffre et al. 2017). However, when experience within the general population about a specific technology is limited, more information often induces negative attitudes and highlights only the risk associated with technologies (Leathers and Smale 1992). Hence, information packages should be audience specific, timely, and bundled with both benefits and risks of the technologies (Joffre et al. 2017).

Characteristics of the Technology

The characteristics of the technology itself clearly play an important role in a farmer's decision to adopt a new technology. However, that decision is more complex than it might appear on the surface. For example, a number of studies have indicated that the individual's decision to adopt new technology is mainly based on personal perceptions (Beal et al. 1957; Deutschmann and Borda 1962; Rogers 1962; Davis 1989) that may differ from what is reported in research findings, promotional materials, and/or real costs (Brickell 1976). Rogers and Shoemaker (1971) identified five distinct attributes (relative advantage, compatibility, complexity, trialability, and observability) that accounted for 49–87% of the variance in decisions by farmers to adopt new technologies (Rogers 1995; Ghadim et al. 2005).

Relative Advantage

Relative advantage (Rogers 2003) is the degree to which a technology is perceived as being superior to the one it supersedes. This characteristic of a new technology will influence its adoption, particularly if it is perceived to have more utility in terms of productivity, cost effectiveness, or riskiness (Batz et al. 1999).

Improvements in productivity (i.e., increased kg/ha of production) have been a key driver in the adoption of new technologies. Productivity changes the farm's production function through either increased output from a given level of input usage or from the reduced use of inputs for the same level of output (Mansfield 1961). Well-known examples of output-increasing technologies in agriculture include increased yield of hybrid corn (Griliches 1957) and new rice/wheat varieties in India (Swaminathan 1969). Improved use of water (productivity gain through reduced use of an input) was identified as the central reason behind adoption of precision-leveling and automated-irrigation systems (Feder et al. 1985).

In aquaculture, nutritionally balanced feed formulations, efficient aeration devices, genetically superior fingerlings, superior production systems, and better disease management have contributed to increases in aquaculture yields (Engle 1989; Asche 2008; Kumar et al. 2016; Kumar and Engle 2017a). These innovations increased the supply of aquaculture products and increased the economies of scale and scope, while reducing the cost of production and consumer prices (Asche et al. 1999; Nilsen 2010; Sandvold 2016, 2018).

There are a number of species-specific technologies that have enhanced productivity in aquaculture. In Atlantic salmon, vaccination proved to be an effective disease-management tool for increasing the survival and productivity in net pens (Sommerset et al. 2005). For tilapia, the higher productivity of genetically improved farmed tilapia (GIFT) achieved through faster growth rates was critical for its adoption in Asia (Dey 2000; Dey et al. 2000a, 2000b, 2000c). In shrimp, development and dissemination of domesticated specific pathogen free (SPF) broodstock of white-legged shrimp, *Lithopenaeus vannamei*, resulted in greater productivity of shrimp production and resulted in a shift away from use of black-tiger shrimp, *Penaeus monodon* (Lebel et al. 2008, 2010). Improved breeding and hatchery practices resulted in productivity increases and rapid adoption of carp production in Asia and striped catfish production in Vietnam (Waite et al. 2014).

New, more productive production systems have also resulted in productivity increases that led to their adoption on farms. Examples include biofloc (Avnimelech 2009) and marine cages for production of Atlantic salmon (Asche et al. 1999). The greater productivity of alternate catfish production systems over traditional farming methods was the primary reason behind their adoption in the US catfish industry (Kumar 2015; Kumar and Engle 2017a, 2017b).

The magnitude of difference in productivity between existing and new technologies has been shown to influence adoption of new technologies (Rogers 1962; Rogers and Stanfield 1968; Zepeda 1994). This relationship is explained alternatively by two theories. One is that the more productive firms are likelier to adopt new technology, while the alternative hypothesis is related to technology leapfrogging, wherein less productive firms switch to a better technology more often than the productive ones (Brezis et al. 1993; Wozniack 1993).

For example, highly productive salmon net pens have evolved by continuously adopting complex management practices that promote growth, compliance, and environmental sustainability (Asche et al. 2015). More productive shrimp farms were found to rapidly incorporate newer aeration technologies (Kumar and Engle 2016) and adopt probiotic-based farming (Moriarty 1998; Gatesoupe 1999; Kumar and Sharma 2001; NCAEPR 2003).

Alternatively, new Norwegian firms entering a highly innovative salmon industry were able to leapfrog technologically over incumbent firms by adopting productive smolt production and hatchery techniques that were previously nonexistent without having the burden of previous investments in older technologies (Nilsen 2010; Sandvold and Tveterås 2014; Sandvold 2016, 2018). Major Norwegian Atlantic salmon operations employ tools such as marker-assisted selection and gene-mapping technologies for selecting broodstocks for improved growth, disease resistance, and processing yield (Gjedrem 2010; Yue 2014; Marine Harvest 2017).

However, when farms switch to a new production technology, there often is an initial drop in productivity due to (1) incomplete transfer of knowledge and experience, (2) the initial costs associated with the learning curve, (3) management and organizational changes needed, or (4) the need for development of complementary investments (Mansfield 1961). The initial production uncertainties associated with new technologies diminish over time as users become more proficient in the application of the technology (Salter 1960).

The cost effectiveness of the new technology is a clear factor in a farmer's decision to adopt a new technology (Katiha et al. 2005). New technologies affect costs and cost effectiveness in several ways, depending on the extent of up-front capital investment required and whether the new technology primarily affects annual fixed or variable costs.

Technologies that require high up-front costs will typically have slower rates of adoption (Parente and Prescott 1994; Jovanovic and Nyarko 1996). Conversely, greater numbers of farmers will be likely to obtain capital required for adoption if the proposed technology requires lower investment costs (Caswell et al. 2001). In general, technologies with high up-front capital investment costs are often accompanied by long payback periods and are often perceived as having lower overall benefits (Pannell et al. 2006).

Lower up-front costs facilitated the introduction and dissemination of integrated aquaculture agriculture (IAA) in developing countries (Dey et al. 2010). Lower capital requirements for integrated rice-fish farming made it easier to experience the improvements brought through the introduction of fish as a biological agent for pest control and soil fertility enhancement (Xie et al. 2011). Similarly, low initial investment stimulated the integration of aquaculture practices with livestock components in Vietnam (Nhan et al. 2007).

In contrast, adoption of aquaculture technologies can be inhibited if the initial cost of investment is high. This may contribute to the slower adoption of aquaculture technologies such as recirculating aquaculture systems (RASs) (Zucker and Anderson 1999; Losordo and Westerman 2007; Ngoc et al. 2016a, 2016b), offshore aquaculture (Rubino 2008), and aquaponics systems (Rupasinghe and Kennedy 2010; Engle 2015; Love et al. 2015; Tokunaga et al. 2015; Bosma et al. 2017). Similarly, the high up-front cost associated with alternate catfish production technologies was the primary producer-cited reason for their nonadoption (Kumar 2015).

Yield-increasing inputs, such as hatchery-reared fingerlings, hybrid fish, and genetically selected strains, tend to reduce the average fixed costs of aquaculture production. Higher yields and cost efficiencies associated with using tilapia hybrids, genetically selected Atlantic salmon, and domesticated SPF white-legged shrimp led to their greater adoption in intensive culture practices (Kumar and Engle 2016).

Technologies that reduce average variable costs for any given yield tend to be adopted more widely (Feder et al. 1985; Douthwaite 2002; Hall and Khan 2003). For example, improved biosecurity approaches in the Norwegian salmon industry have reduced the reliance and cost on antibiotics and chemotherapeutics (Sommerset et al. 2005; NDF 2015). Improvements in feed formulations have led to the development of salmon and shrimp diets with improved feed conversions and reduced reliance on fishmeal and fish oil (Tacon and Metian 2008; Tacon et al. 2011). Nutritionally balanced all-plant sources have completely spared the use of fishmeal in tilapia (Watanabe et al. 2002) and channel catfish diets (Li et al. 2002, 2017).

Risk – both the measurable variations in market prices, yields, and input costs and those perceived by farmers – will affect whether a farmer chooses to adopt a new technology (Tsur et al. 1990). The riskiness of a new technology may reduce relative advantage of an innovation in the minds of farmers and inhibit its adoption (Ghadim and Pannell 2003; Marra et al. 2003; Ghadim et al. 2005). Thus, greater variability in yield, survival, or returns often deters producers from adopting new technologies (Feder 1980).

The risk of lack of access to sufficient supplies of Pacific threadfin fingerlings may have inhibited development of offshore farming of this species in Hawaii (Kam et al. 2003). Catfish producers adopted multiple-batch production practices even though single-batch production was more profitable due to reduction in risks associated with cash flow (Engle and Pounds 1993) and marketing (Engle et al. 1995) when fish were grown in multiple-batch culture. Increased financial risk resulting from a higher fingerling price was attributed as the main deterrent for the initial adoption of hybrid catfish in traditional catfish farming systems (Kumar and Engle 2010, 2011).

Farmers, as well as other individuals, vary in terms of their reactions to risk, a key factor explaining the various adopter categories

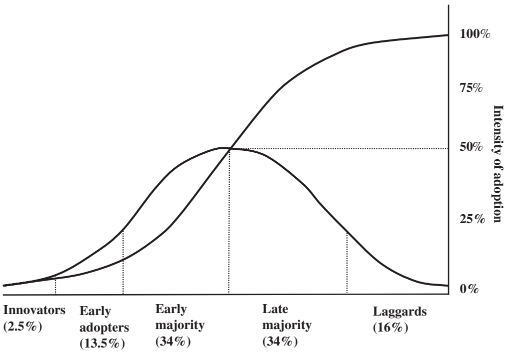

FIGURE 2. *Sigmoid cumulative process of diffusion. Source: Rogers (1995).*

(Fig. 2). A more risk-averse farmer is more likely to adopt technologies that are perceived to reduce risk, whereas a risk-taking farmer might seek out risky technologies if there is a chance of high returns (Deutschmann and Borda 1962; Binswanger 1980; Just and Zilberman 1983; Ghadim et al. 2005). Tveterås (1999) found that risk-averse salmon firms tended to adopt lower scales of operation with less intensive feeding and stocking rates and employ more labor than did risk-neutral firms. Shrimp farms in Vietnam are coping with risk in shrimp farming by adopting practices, such as crop and species diversification, involvement in cooperatives, integrating aquaculture and agriculture, redesigning farms, and adopting organic standards (Ha et al. 2013). Bunting et al. (2013) found that shrimp farmers of Mahakam delta, Indonesia, may not adopt the semi-intensive practices because its benefits are about equal to the extensive practices, while the latter bears lesser financial and investment risk. Nonadopters of alternate catfish production technologies were more risk averse and were concerned about the variability in yield and prices (Kumar 2015). Risk-averse farmers may seek out and adopt technologies that reduce market risk through species or crop diversification (Dey et al. 2010) or by adopting technologies that reduce the incidence of disease, as in the case of shrimp production in Latin America (Valderrama and Engle 2002).

New technologies are often associated with risk of increased regulatory prerequisites (Millman and Prince 1989; Ecchia and Mariotti 1994). Firms that incur lower transaction costs in gathering information about the newest technologies found it more profitable to adopt new technologies than firms with higher search costs (Blackman 1999). The regulatory environment can increase risk through uncertainties related to obtaining permits and licenses or the fear of unexpected changes in compliance requirements (Kam et al. 2003). In the USA, the multitude of overlapping local, state, federal, and regulatory agencies have created a complex, uncertain, and risky environment (Jensen 2007; Engle and Stone 2013; Abate et al. 2016; van Senten and Engle 2017) that has inhibited adoption of new aquaculture technologies (Kite-Powell et al. 2013; Osmundsen et al. 2017). Increased risks arising from regulatory burdens were also cited as key reasons for stagnation of semi-intensive shrimp farming in Honduras (Valderrama and Engle 2002) and mariculture in the EU (Bostock et al. 2009).

Compatibility

Compatibility refers to the degree to which a technology is perceived to meet needs of potential adopters (Rogers 1995). For example, the adoption of hybrid sorghum was found to be more compatible with farmers who had already adopted hybrid corn (Branden and Straus 1959). Similarly, sophisticated farm vehicles and equipment were found to be more compatible with younger groups of adopters rather than older groups of adopters (Ettlie 1979). In general, an idea that is more compatible would align more closely to a potential adopter in terms of value, past experience, and innovation need.

New aquaculture technologies must be compatible with the local, ecological, and social conditions into which it is being adopted (Lovshin et al. 1986; Molnar et al. 1996; Pomeroy et al. 2014). Thus, integrated farming and polyculture practices were better received in developing countries such as Malawi as these practices were compatible with the existing agro-farming practices of the region (Pullin 1993).

Social compatibility is often compromised when the expansion of aquaculture limits the opportunities and livelihoods of other community residents. Although the state of Alaska in the USA holds tremendous resource potential for salmon farming, local and national interest groups cite social and cultural incompatibilities to oppose this opportunity (Knapp et al. 2007). High levels of public concern about genetically modified organisms in the EU markets show a lack of compatibility with production of transgenic fish that will likely inhibit adoption of such technologies (Bostock et al. 2009).

Complexity

Complexity of innovation, or the relative degree to which an innovation is perceived as difficult to understand and use, has a negative relationship to its adoption (Rogers 1995). Technologies are adopted more quickly if they are easy to understand and use; consequently, farmers typically prefer to adopt less-complex innovations over more-complex ones. In aquaculture, integrated aquaculture and polyculture practices were adopted in Panama and Malawi due to their relatively lower degree of complexity (Pullin 1993). Complexities arise depending on the degree and extent of change required from the traditional technology or management (Henderson and Clark 1990). These can be (1) incremental changes to existing technologies, (2) modular changes to management process without change in the technology designs/components, (3) design changes that require change in management, and (4) radical innovation where the technology and management are profoundly different (Joffre et al. 2017).

Complexities associated with aquaponics technologies are seen as an important hindrance in its adoption in Europe (Bosma et al. 2017) and the USA (Engle 2015; Tokunaga et al. 2015). Such complex systems often require complementary skills in bioengineering and animal and plant husbandry. However, complex new technologies, such as the algorithm-based automated-feeding systems and video-monitoring systems in Norwegian salmon net pens, have been adopted despite the complexity due to improved efficiencies associated with feeding and labor (Kumar and Engle 2016).

Trialability and Observability

Trialability is the ability of users to experiment with an innovation. It helps early adopters to answer doubts about how an innovation might work under their farming conditions. Technologies that can be tried on an installment basis in limited space and time will be adopted more often and more quickly than less-trialable innovations (Rogers and Shoemaker 1971). An innovation that is more visible will stimulate communication among farmers and often lead to greater adoption (Vanclay 1992). For example, Abara and Singh (1993) suggested that small-scale rice farmers adopted new varieties only after observing significant yield improvements. Trialability and observability are directly related to the rate of adoption and are important factors influencing adoption decisions of early adopters (Rogers 1995).

In aquaculture, technologies, such as new strains or hybrids of fish, that can be experimented with relatively easily in just a small area of the farm tended to be adopted more widely (Dey et al. 2010). Farmers can adopt such technologies in a stepwise manner and observe the benefits of growth, survival, and feeding efficiencies. Adoption of several types of aerators (long-arm and spiral) in the Asian shrimp industry also followed this sort of sequential trial adoption pattern in which model demonstration ponds in specific regions acted as platforms for trial and observation (Lebel et al. 2016).

Divisibility

Divisibility of an innovation refers to whether a new technology can be used on a limited basis and if a specific subcomponent of an innovation package can be implemented (Arrow 1962; Leathers and Smale 1992) for small-scale trialing and partial adoption (Vanclay 1992). Farmers can adopt those parts of an innovation that they like or that are consistent with other farming objectives. Technologies that require high initial capital investment and that result in high fixed costs tend to be much less divisible (Feder and Umali 1993).

Divisible technologies (such as hybrid catfish or GIFT tilapia) entail mostly variable costs, while an indivisible (lumpy) technology (such as a RAS) has an initial investment cost and a greater annual fixed cost that must be covered. Even when an innovation package is promoted to farmers as a tightly bundled package, farmers have a strong propensity to pull it apart and either adopt only some of its components or modify selected components (Wilkinson 1989). Adoption of several designs of water circulators in catfish split-pond systems (Kumar et al. 2016) is an example in which farmers modified the water circulators in the original research design with less-expensive paddlewheels or with different types of water pumps to suit their farming and cost objectives. Additionally, commercial modifications of the split-pond systems have been currently adopted in baitfish and largemouth bass industries (Park et al. 2014; Smith and Stone 2017) to serve purposes other than yield increase, such as achieving better-conditioned and uniform-sized fish.

Complementarity

Innovations are often perceived as tightly interrelated bundles of existing, modified, or new ideas. Hence, adoption of new technologies may be enhanced by the presence and availability of complementary technologies (Lionberger 1960). Complementarity ascends when one technology aids the adoption of another (technology complementarity) or when one input aids the adoption of another input or technology (input complementarity). Early adoption of hybrid and selected crop strains were directly influenced by the existence of complementary mechanical infrastructures, such as tractors, precision leveling, and irrigation systems, and by the use of complementary inputs such as inorganic fertilizers (Feder et al. 1985).

Improved feeds and fingerlings, availability of skilled labor, and transportation are critical complementary inputs that have influenced technology adoption decisions in aquaculture. Input complementarity between use of higher quality diets on farms with better infrastructure (i.e., electricity, generators, aerators) were observed in shrimp and milkfish farming (Chiang et al. 2004). Kumar (2015) identified the existence of technology complementarity between the use of hybrid catfish and adoption of intensive catfish production technologies. The greater yield potential of hybrid catfish served as an incentive for its use in intensive-production systems. Similarly, automated oxygen monitoring systems also served as complementary technology aiding adoption of indivisible productive systems in the US catfish industry.

Economic Factors

Farm activities that increase farm income, alleviate economic and financial risk, and reduce labor requirements are pursued to improve the farm utility and/or well-being (Barnum and Squire 1979). Economic factors such as the expected profits, input and output prices, availability of investment and operating capital, and labor availability influence the adoption of new technologies. Producers who expect to obtain greater profits from the new technology are likelier to adopt it (Stoneman 1991). In agriculture, expectations of greater profits resulted in greater adoption of high-yielding rice varieties (Pitt and Sumodiningat 1991), new legume crops, chick peas (Ghadim et al. 2005), and conservation technologies (Cary et al. 2001).

Profitability

Griliches (1957) suggested that the rate and extent of adoption is directly related to the profitability associated with technologies. In aquaculture, expectation of greater profits from integrating aquaculture with agriculture was an important reason for adoption in Malawi (Dey et al. 2006, 2010). The expectation of greater profits driven by the increasing demand for black-tiger shrimp in the US and Japanese markets resulted in adoption of more intensive shrimp production practices in Asia (Csavas 1994; Keefe and Jolly 2001). Similarly, strong commercial intent and expectations of greater profits were important determinants of the adoption of shrimp farming in India (Katiha et al. 2005) and tilapia farming in Cameroon (Wandji et al. 2012). Greater profit expectations from green-water culture system (culturing fish species in reservoir ponds that feed shrimp ponds) were identified as the primary reason for its adoption among shrimp farmers in the Philippines (Bosma and Tendencia 2014.) Similarly, expectation of greater profits was identified as a main reason for early adoption of alternate catfish production technologies (Kumar 2015).

Input and Output Prices

Market prices influence the progress and direction of technology adoption by affecting the relative profitability of technologies (Griliches 1957; Feder et al. 1985). A variety of studies have also examined the role of output price on technology adoption (Rosenberg 1972; Kislev and Schori-Bachrach 1973; Feder 1980; Just and Zilberman 1983; Stoneman and Ireland 1986). Higher output prices generally serve as an incentive to increase production (Feder et al. 1985; Pitt and Sumodiningat 1991). Kumar and Engle (2017b) showed that under conditions of stable output prices, all other things held constant, the proportion of land allocated to yield-increasing technologies such as split-pond systems increases on catfish farms. However, under conditions of lower or unstable outprices, risk-reducing technologies such as intensive aeration systems are preferred alternatives (Kumar 2017).

When prices are high, producers generally tend to adopt practices that maximize yield (Losinger et al. 2000; Kumar 2015). Technologies used to produce *Pangasius* (Basa, Tra, Swai) in Vietnam for export and channel catfish culture in China and Thailand were adopted primarily in response to greater prices in the US markets (Quagrainie and Engle 2000; Singh and Dey 2011). The shift from traditional "latrine ponds" to supplemented feeding operations in Vietnamese catfish industry was primarily to benefit the profitability of export markets (De Silva and Phuong 2011). Profit incentives led to the development of deeper ponds that facilitated the storage of sludge rather than its discharge. Species of choice among aquaculture farmers in Tanzania were found to be significantly influenced by the price of fish and the premiums associated with size (Wetengere 2011). Brazil is placing greater emphasis on development of aquaculture technologies for native species that command greater prices in domestic as well as international markets (Pincinato and Asche 2016).

Control over the aquaculture production process often provides relief from price volatility, at least as compared to wild-caught seafood products (Asche 2008; Asche et al. 2015). However, technology-induced supply surges have reduced the real (adjusted for inflation) and relative prices (compared to beef or pork) of several aquaculture products such as shrimp, salmon, and tilapia (Smith et al. 2010). Kumar (2015) found that farmers delayed decisions on technologies to wait for less volatile market conditions. Similarly, lower farm-gate price and higher feed prices reduced the interest in input-intensive-farming practices among tilapia farmers in Thailand (Belton et al. 2009) and catfish farmers in the USA (Engle 2010; Kumar and Engle 2014).

Faster dissemination of technologies is strongly correlated to low prices of inputs that are used intensively by adopters (Jarvis 1981). When input prices are high, technologies that tend to lower or improve efficiency of use of such inputs are preferred and adopted (Sunding and Zilberman 2001). Feder et al. (1985) suggested that prices of seed, fertilizers, and pesticides played an important role in adoption of high-yielding varieties (HYV) during the green revolution in developing countries. Increased interest rates are known to negatively affect technology adoption by increasing operational costs as well as by discounting future profits (Tsur et al. 1990).

Greater availability of less-expensive hatchery-supplied shrimp postlarvae (PL) was essential to the rapid dissemination of semi-intensive and intensive shrimp farming (Csavas 1994). Increased feed prices forced catfish farmers to adopt suboptimal feeding and stocking strategies (Kumar and Engle 2014). Similarly, prices of feed were found to influence the extent and intensity of adoption of alternate catfish production technologies (Kumar and Engle 2017b).

Availability of Capital

Farms without adequate investment or operating capital will not be able to adopt new technologies (Salter 1960). Aquaculture is often capital intensive, and few farms have the capability to provide all the capital required for investing in new technologies (Engle 2010). Kumar and Engle (2017b) showed that lack of available capital can impede the adoption of newer, more profitable technologies. Capital constraints inhibiting the procurement of productive inputs such as hatchery-raised PL, pumps, and quality feed were found to limit the adoption of high-quality feed and semi-intensive shrimp farming in Indonesia (Yi et al. 2016).

One way to overcome constraints of capital availability is through borrowing, and access to credit is considered an important factor that influences the adoption of agricultural technologies (Feder et al. 1985). Timely provision of credit induced adoption of practices that increased soybean production in Brazil and rice production in India (Herzog 1972). Parente and Prescott (1994) found that the majority of small farms reported capital constraints as a reason for not adopting lumpy technologies.

Lenders often view aquaculture as a high-risk business, with fewer lenders familiar with aquaculture technologies. Funding from the World Bank and local government subsidies contributed to the early adoption of shrimp-farming technologies in several Asian countries (Boyd 2002; Asche et al. 2015). However, the major credit for propagation of shrimp farming in Asian countries goes to the multinational feed manufacturers. Prior to starting feed mills, these international firms identified and attracted collaterally strong regional feed dealers through sales-based incentives to promote the provision of expensive shrimp feeds on credit to shrimp farmers.

Labor Availability

Adoption decisions are often dictated by availability of labor. Dynamics and seasonality of labor availability often dictates the extent of adoption of specialty crops that have narrow harvesting windows or that require high labor (Binswanger and Rosenzweig 1986). Hence, farms tend to adopt labor-saving technologies when labor is sparse and/or when wages are high. Innovations that automated the process of feeding and monitoring in offshore salmon net pens were widely adopted despite their high investment costs as they minimized labor and production costs and technically reduced the labor force to a few highly skilled operators (Asche et al. 1999). Automated oxygen monitors have also been widely adopted in the US catfish industry (Kumar 2015) as they improve labor efficiencies.

In contrast, labor-intensive technologies are more likely to be adopted when labor is abundant and inexpensive or when the opportunity cost of labor is low (Shields et al. 1993). Ahmed et al. (1995) and Pemsl et al. (2006) found that the probability of adoption of aquaculture technologies was higher for households with farming as their principal occupation or for those using their own labor for farming needs. In Malawi, aquaculture practices that required less labor were adopted faster (Mills 1989). Dey et al. (2010) found that adopters of integrated aquaculture technologies in Malawi had greater returns to family labor than nonadopters of technologies.

Availability of a sufficiently large and low-cost labor force with low opportunity costs of labor aided the development of shrimp farming in Asia (Keefe and Jolly 2001). Semi-intensive aquaculture practices in Asia were found to increase the marginal productivity of labor and provided more income, employment, and food securities to rural households (Ahmed and Lorica 2002). Rubino (2008) suggested that offshore aquaculture is likely to be highly mechanized and will utilize relatively fewer, but more skilled, workers than onshore farming. Technologies such as automated feeders, video monitors, and cage cleaners were adopted by offshore salmon net pens primarily to improve labor efficiencies (Asche 2008). Mechanical shrimp-harvesting systems are increasingly popular in intensive shrimp farming due to their ability to reduce harvest labor and to improve the quality of harvested shrimp (Hodgson et al. 2000; Cline 2013).

The availability of leisure time is also identified as an important factor affecting technology adoption. In general, practices that draw heavily on a farmer's leisure may inhibit technology adoption (Shields et al. 1993; Wabbi 2002). Aquaculture practices that leave time for off-farm income generation may be adopted faster (Mills 1989). However, off-farm employment may impede adoption of technologies that require greater management demands (Kebede et al. 1990). Producers who had greater family labor and full-time commitment in soft-shelled crab farming had greater likelihood of adopting management-intensive technologies such as RAS (Caffey and Kazmierczak 1994).

Farm Characteristics

Farm Size

Most of the empirical literature on technology adoption in agriculture tests the Schumpeterian hypothesis that large firms are both more innovative and faster to adopt new technologies than small firms. Several of these studies focus on farm size as the first and probably the most important determinant. "Scale-dependent" technologies, such as tractors, mechanical harvesters, and precision irrigation, were found to be adopted earlier by larger farms (Globerman 1975; Romeo 1975; Feder et al. 1985). Farm size was found as the most significant factor influencing adoption of HYV (Feder et al. 1985), inorganic fertilizers (Kebede et al. 1990), and irrigation technologies (Gafsi and Roe 1979). Adoption of indivisible technologies was found to be greater on larger farms (Abara and Singh 1993). Feder et al. (1985) suggested that farm size may be a proxy for better access to inputs (credit, capital, and labor), information (human capital), ability to bear risks, technical efficiency, and financial flexibility.

Cost efficiencies related to scale are found in aquaculture industries with high capital investments (Engle 2010). Bailey et al. (1997) reported scale efficiencies related to the adoption of improved pumps and automated systems in larger net pens. Similarly, better resource availability and financial flexibility of larger farms led to increased adoption of integrated aquaculture technologies in Vietnam (Nhan et al. 2007; Bosma et al. 2012).

Larger farms have often been found to be more technically efficient and able to adopt technologies that further increase productivity. Greater technical efficiency observed on larger farms in the Philippines resulted in adoption of semi-intensive tilapia culture practices (Dey 2000). Improved production efficiencies over time in the salmon industry have been credited to firms becoming larger (Asche et al. 2013; Asche and Roll 2013). Early adopters of BMP and environmental certification were observed on larger vertically integrated shrimp farms (GAA 2006). Similarly, probability of adoption of alternate catfish production technologies such as split ponds and intensive aeration were found to be greater among larger catfish farms (Kumar 2015). Salazar et al. (2018) showed that larger Chilean aquaculture firms tend to innovate in more areas of production as opposed to smaller firms.

However, the effect of farm size on adoption of technologies declines over time as the perceived output variance associated with the new technology diminishes (Feder et al. 1985). Ruttan (1977) found that smaller farms that initially lagged behind larger ones in adopting HYV eventually caught up. Similarly, where the availability of suitable land is low and when most farms are smaller, land-saving technologies were adopted on a smaller farm (Yaron et al. 1992).

Ownership and Tenure

Several studies suggest that the nature of land ownership plays an important role in adoption decisions. In developing countries, owners of land often serve as credit providers hindering adoption of yield-increasing innovations in fear of reduced tenant indebtedness in the future (Bahduri 1973). Such cases promote adoption of land-augmenting and labor-intensive technologies (Bardhan 1979). Similarly, short-term rental contracts may significantly deter adoption of technologies even when perceived to have future benefits (Blackman 1999). However, Sunding and Zilberman (2001) found that the existence of long-term rental relationships may accelerate technology adoption on large-scale farming operations, although the same does not appear to hold true for small-scale operations (Feder et al. 1985).

Land ownership and tenure issues were cited as one of the principal constraints faced by nonadopters of aquaculture in Zambia (Harrison 1995). Although secure land tenure alone may not explain aquaculture adoption, longer tenure tended to positively influence farmer decisions to invest in pond construction on agricultural lands that have alternative uses (Roth et al. 1992). Limited ownership of land was found as an important factor inhibiting the adoption of advanced aquacultural activities in rural India (NCAEPR 2003; FAO 2005). Owner-operated farms were found to adopt improved technologies on shrimp farms in Thailand, while tenure agreements were found important for tenants for adoption of extensive aquaculture operations in India (Dey et al. 2005). Edwards (2000) and Silas et al. (2011) showed that resource-poor societies in Asian countries often pool resources to do farming of seaweed, mollusks, and ornamental fish that require less land. Small-scale Indonesian aquaculturists were entangled in patron–client relationships and were found to be less efficient in adopting semi-intensive shrimp-farming practices (Bunting et al. 2013). Adoption of inland aquaculture practices such as rice-*cum*-fish farming and cage culture among poor ethnic societies in Bangladesh (Pant et al. 2014) was primarily attributed as they had lesser land holdings. Similar tenure security concerns were also observed with nonadopters of alternate catfish production technologies (Kumar 2015). Land owners finding greater opportunities for their land may not issue longer tenure to tenants, which in turn reduces incentives to adopt technologies such as split ponds that require substantial structural pond modifications and up-front investment.

Sociodemographic and Institutional Factors

Age

There is no clear consensus on the effect of age of the adopter on adoption decisions. Accumulation of knowledge and experience with farming systems obtained from years of observation and experimentation by older farmers is thought to positively influence technology adoption (Shields et al. 1993). Age was found to contribute positively to adoption when farmers' education and experience levels were higher (Feder et al. 1985). However, the majority of the adoption literature suggests that age is a constraint to technology adoption. Rogers (1995) classified "technology laggards" as a characteristically older group who tend to view newer technologies skeptically. Younger farmers were more likely to adopt newer technologies for the same level of capital availability and labor availability (Rauniyar and Goode 1992). Wabbi (2002) found that elderly farmers often have goals other than profit maximization and would not be expected to adopt yield-enhancing technologies.

The negative influence of age of adopters was found with adoption of new aquaculture technologies in Africa (Harrison 1995), shrimp farming in Asia (Keefe and Jolly 2001), soft shell crab farming in the USA (Caffey and Kazmierczak 1994), and semi-intensive tilapia and carp faming in Asia (Pemsl et al. 2006; Iliyasu and Mohamed 2015). The level of understanding and awareness of changing aquaculture practices were lower among older farmers in Bangladesh (Alam et al. 2012). In most of these cases, technologies that are likelier to produce results in the future were rejected by older farmers.

Human Capital

Human capital variables (the ability to acquire and process complex information) such as education, technical skills, and experience also influence adoption decisions. Farmers with better education were earlier adopters of modern technologies and efficiently applied more modern inputs in the production process. The availability of skilled human capital allows for stronger learning by doing and the ability to reduce technology complexities, leading to better chances of adopting newer technologies (Spenser and Byerlee 1976). For example, the likelihood of adoption of high-yielding wheat varieties in India and hybrid maize in Kenya was positively related to the levels of education and the technical skills of farmers (Feder et al. 1985).

Aquaculture farms with excellent human capital are often observed to be technically efficient. Such farms have improved productivity and skills for accommodating new management practices (Dey et al. 2005). Lack of human capital was attributed as the reason for high degrees of production inefficiencies associated with subsistence and less-intensive aquaculture production practices in Asia (Dey et al. 2008). The level of education of farmers and available labor skills were found to positively influence the adoption of fish-farming practices in Cameron (Wandji et al. 2012). Similar observations found in the aquaculture literature portray a positive influence of the farmer's level of education, experience, and technical skill on farm economic efficiencies (Irz and Mckenzie 2003; Kaliba and Engle 2006; Dey et al. 2008; Singh et al. 2009; Iliyasu and Mohamed 2015). Bosma et al. (2012) showed that educational levels of farmers were an important determinant in the adoption of integrated rice-fish culture in Vietnam. Similarly, technology usage among small-scale aquaculture firms in Chile was found to be positively linked with their level of education (Salazar et al. 2018). In general, the availability of human capital is found to reduce the complexity associated with aquaculture farming practices and fuel the adoption of better management systems.

Location

Proximity to regions of technological evolution and development facilitates interaction, information exchange, and technological learning (Stoneman 1991). Knowledge about a technology is more easily transmitted among users when they are close rather than when far apart. As these transactions become more complex and costly with distance, economic activities from technology innovations tend to be geographically clustered (Baptista and Swann 1998), leading to time-clustered adoption (Au and Kauffman 2005).

Evidence of localized adoption of aquaculture practices is common in Asian countries where communication and interaction are often limited. Shrimp-feed companies such as CP Group propagate technologies, management practices, and products in a farming community by selecting a local collaborating farm as demonstration farm. This allowed for the dissemination of efficient aeration devices and biosecurity practices (Pananond 2006; Lebel et al. 2010). Similarly, yield-increasing practices for milkfish were better disseminated in the Philippines through organization of village-level farmer groups (WFC 2007).

Proximity to early adopters (Molnar et al. 1985), research stations involved in technology development and demonstration (Kumar 2015), fingerlings and feed suppliers (Csavas 1994), suitable resources such as land and water, and postharvest facilities and marketing opportunities (Engle 1989, 1997a, 1997b) facilitated localized adoption of several farming systems. Many of these factors contributed to regional-level development of baitfish farming in Arkansas (Stone et al. 2016), channel catfish farming in southern USA (Tucker and Hargreaves 2012), and crayfish farming in Louisiana (McClain et al. 2007).

Homogeneity

Communication among individuals is a key element of technology diffusion (Rogers 1995). Efficient transfer of ideas and technology diffusion occurs more frequently when the communicating individuals are more similar. Spread of information is relatively easier in homogenous societies due to the existence of information cascade, a phenomenon that makes the members in a society to follow the heard leader (Watts 2002). When given a choice, individuals usually choose to interact and communicate with a group with similar beliefs, education, and social status.

Introduction of technologies without proper understanding of the socioeconomic framework of a society will often result in poor dissemination of aquaculture technologies (Lovshin et al. 1986). Economic inequalities and lack of homogeneity within farmer groups were the main reason for the failure of dissemination of aquaculture technologies in Panama (Schwartz et al. 1988). Fish farmers in Malawi were found to increasingly depend on neighboring adopters for technology information (Pemsl et al. 2006). Transfer of seaweed farming technologies in countries such as India, the Philippines, Indonesia, and Tanzania were faced with cultural, ethnic, and language barriers (Valderrama et al. 2013). In such circumstances, knowledge dissemination was found to be more effective when delivered to smaller groups of farmers who were socioeconomically similar.

Policy Interventions

Government policies can often influence technology decisions made by farmers. Policy interventions such as credit programs, input price subsidies, buy-back systems, and subsidies on the cost-per-ha basis provide incentives for technology development among early adopters (Feder et al. 1985). Governmental price stabilization (Caswell and Zilberman 1986) and provision of risk-bearing credit systems and affordable lending rates induced technology adoption (Tsur et al. 1990). However, provision of subsidies is often debated as it does not necessarily increase economic welfare (Binswanger 1980; Stoneman 1991). Provision of paid services offered to producers is considered more effective than providing direct subsidies as producers tend to value future benefits less than current ones (Duflo et al. 2004). Moreover, the provision of uniform regulatory standards would foster cooperation across firms and countries. This is where governmental agencies have the greatest impact as it promotes both product and process innovations (Suriñach et al. 2009).

Gupta et al. (1999) reported a more than sixfold increase in aquaculture production following developmental initiatives in Asia during the early 1990s. Policies targeting small-scale and subsistence farmers were identified as key factors influencing aquaculture adoption (Ahmed and Lorica 2002). Early coordinated engagements by federal and state agencies along with universities led to the development of a sustainable baitfish industry in Arkansas. Resultant culture methods, hatchery technologies, and biosecurity practices reduced the unsustainable harvest of baitfish from natural waters (Stone et al. 2016). Streamlined regulatory processes in the Norwegian salmon industry have internalized several externalities (Asche 2008; Engle and Stone 2013). The share of native freshwater species in Brazilian aquaculture is increasing as regulatory agencies are providing incentives to stay away from culturing nonnative species such as shrimp and tilapia (Pincinato and Asche 2016).

However, all policy interventions do not produce the intended results. Governmental credits and subsidies provided during the early developmental stages of export-oriented sectors such as shrimp in developing countries did not provide incentives to increase marginal productivity of inputs. This led to the increased diversion of foodfish to fishmeal thus reducing economic welfare. Aquaculture development in several African countries is hampered by the lack of sector-specific development policies and plans. Input subsidies provided to the private sector where average wealth is higher often results in a "crowding out" effect while similar interventions in poorer areas where the private sector is relatively inactive would generate a "crowd in" effect (Amankwah et al. 2016). Hence, governments should actively disengage themselves from activities that can be profitably practiced by private farmers (Jamu and Ayinla 2003). This would free up resources that could be made available to focus on areas of importance such as genetic enhancement, artificial spawning, and biosecurity.

Spread of New Aquaculture Technologies

Most of the factors influencing technology adoption identified in the above section are concordant and not mutually exclusive. Hence, they tend to interact in complex ways producing cumulative effects on a farmer's decision-making process. While making the decision to adopt or reject a new technology, individuals often undergo an innovation-decision process (Shannon and Weaver 1949), which characteristically involves five distinct stages: awareness, interest, evaluation, trial, and confirmation. In the awareness stage, the individual is exposed to the innovation but lacks complete information about it. During the next stage, the individual develops interest in the new idea and seeks additional information about it. The evaluation stage is a mental decision-making phase where one engages in activities leading to a trial stage in which the individual experiments with the innovation for the first time. This leads to the confirmation stage where the individual reinforces an adoption decision. However, the decision made may very well be reversed if exposed to conflicting messages about the technology (Vanclay 1992). This individual innovation-decision process is key in understanding the societal process of spread of new technologies.

Although specific studies related to aquaculture technology dissemination are lacking, sociologists have proposed several theories that could help understand how technologies spread in their respective sectors. Several theories detail the technology dissemination process, differing based on the nature of agents (societal players), type of innovation, communication channels, and degree of societal complexities involved. All these theories essentially describe ToT as a process involving communication between information donor(s) and recipient(s). Some of the noteworthy ones are highlighted below.

The theory of planned behavior (Ajzen 1985) links beliefs and behavior and suggests that there are rational reason/action(s) behind individual decisions. Expectations about technology performance and ease of use collectively shape an individual's intentions. Similarly, cognitive learning theories suggest that individuals acquire knowledge by observing others' successes or failures (Bandura 1986). The technology acceptance model (Davis 1989) posits that an individual's intention to use a technology is determined by the perceived technology attributes and the latent perceived utilities. This theory was later modified to include the influence of societal and policy environmental factors to postulate a unified theory of acceptance and use of technology (Venkatesh et al. 2003).

Two later theories detailed elements that influenced the way firms/individuals evaluate and adopt new technologies. The technology–organization–environment framework theory proposed by DePietro et al. (1990) emphasized that adoption and implementation of innovations is influenced by the nature of the technology, organization, and environment. The technological context includes both product and processes, while the organizational context refers to the firm characteristics: resources, scale, scope, degree of concentration, managerial structure, and training of employees. The environmental context includes the degree of competition, the policy-fostering nature, and the regulatory framework (DePietro et al. 1990). However, the most popular theory of technology dissemination is the diffusion of innovation (Rogers 1995), which essentially describes diffusion as the spread of a new idea from its source of invention to its ultimate users and considers it essentially as a cumulative-societal process (Fig. 2) comprising several individuals making adoption decisions in their respective societies.

However, diffusion is difficult to quantify because humans and human networks are complex. It is extremely difficult to delineate and measure what exactly caused adoption of an innovation. Modern computational abilities have enabled the development of complex network models that generally contain a variety of autonomous actors, called complex adaptive systems agents (Holland 2006). These agents have distinct behavior, interaction, learning ability, and adaptability to economic environment. Clustering techniques are used to identify nodes among the network of agents in a network and the number of connections of nodes with their neighbors and the presence of a high degree of commonality giving rise to sociotechnical graphs (Latour et al. 1992) that depict their dynamic behavior in an industry. However, in these threshold models, economic terms are determined by the perceived utility of the innovation as viewed by the agent as well as barriers to adoption such as up-front cost (Watts 2002). Complex adaptive models and sociotechnical graphs accommodate the complexity of innovation environments in which the adopter often receives information from multiple sources and sends feedback to technology suppliers, making it a two-way communication model.

Although there is extensive theoretical borrowing from sociology, economists and sociologists are in agreement about some key factors influencing dissemination of technologies. This section elucidates the important commonalities that were found in many of these theories, such as the role of learning, spillover, and technology suppliers in the spread of technologies.

Role of Learning

Griliches (1957) and Mansfield (1961) proved that technology diffusion is a byproduct of the spread of information between potential users and current users. Farmers achieve learning by doing by their own use or by seeing others in practice (Shannon and Weaver 1949; Bandura 1986; Tsur et al. 1990) or through skill achieved and enhanced by reading, listening, and watching (Ghadim and Pannell 1999). The FFS approach promulgated by the FAO and several other global agricultural organizations serves as a dais for learning, experimenting, and exchanging a variety of information (Brown and Ratna 2013). These allow farmers to learn from their own situations, thus effecting technical and economic improvements over their conventional practices (Nandeesha et al. 2012).

Adoption of new technologies does not happen all at once, but in a sequential/stepwise fashion. Involvement of learning about a technology over time makes adopters behave so, thus making the adoption process dynamic (Mansfield 1961). Farmers learn from each other by sharing information about their perceptions and knowledge about technologies prior to making an adoption decision. Early adopters may overadopt in the early periods if they ignore the future costs associated with the technology and overestimate the value of early adoption of the new technology. Adaptive learning of fish farming was observed at subsistence levels under practices such as integrated farming and polyculture in Panama (Molnar et al. 1985) and Malawi (Dey et al. 2008). More experienced farmers showed a greater degree of information processing and strong learning by doing as well as learning from neighbors. Shrimp farmers in Thailand and Vietnam were found to modify their culture practices over time to adjust to changing biosecurity and environmental needs (Lebel et al. 2002). Integration of fish culture to rice cultivation in Vietnam significantly improved over the years as innovative farmers devised new coculture practices and reduced the use of pesticides (Nhan et al. 2007; Bosma et al. 2012).

Shrimp farmers in Thailand and Mexico were found to develop a learning culture through the development of trustworthy sources of information involving multiple supply chain members leading to a continual reevaluation of understanding of the importance of consumer safety and ecological sustainability (Lebel et al. 2016). Similarly, adoption of resource-efficient white-legged shrimp, their domestication, and reduction in effluent discharges were a result of coordinated learning process within the Thai shrimp industry (Lebel et al. 2010). Kobayashi et al. (2015) suggested that the lessons learned from shrimp and salmon industries would be critical for dealing with serious diseases in the emerging aquaculture sectors in Asia and Africa. Evidence from the salmon industry suggests that existing smolt producers were able to generate technical efficiencies through learning by doing (Sandvold 2016, 2018). However, under conditions of high technology competition and rapid evolution, firms with older vintage capital have less time for learning by doing due to technological leapfrogging by newer firms (Nilsen 2010).

Role of Spillover

Technology spillover is the process of movement of beneficial (or sometimes detrimental) knowledge from users to potential users (Baptista 1999; Guettler et al. 2012). It is regarded as the key for eliminating geographical barriers and allows the dissemination of technologies across time and space (Comin et al. 2013). Benefits from R&D technology spill over beyond both spatial and temporal boundaries, to producers, consumers, and other researchers (Alston et al. 1998). Agricultural sectors have strongly benefited from technology spillovers primarily due to complementary development in technologies (Alston 2002). Positive spillovers generated from farmer training and demonstration programs also aided in the diffusion of several agricultural technologies (Caswell and Zilberman 1986).

The relatively infant nature of the aquaculture industry has led to tremendous technology spillover from other agriculture sectors. Mechanization, automation, nutrition, and biotechnology advances in aquaculture spilled over from agricultural and animal husbandry practices. Propagation of several aquaculture species involve sophisticated R&D, better human capital, and global undertakings that attracted the application of better technologies (Duarte et al. 2007). Increased use of soybeans in animal husbandry has led to the development of fishmeal-sparing alternate protein diets in aquaculture (Li et al. 2002). Biotechnological developments such as vaccination and probiotics, hybridization, and selective breeding were positive externalities that spilled over from other animal-husbandry practices. Knowledge and design spillovers from the wastewater-processing industry led to the development of several pond aeration devices (Boyd 1998), RASs (Cripps and Bergheim 2000), and biofloc technologies (Avnimelech 2009). Compartmentalization techniques used in wastewater-treatment plants led to development of Partitioned Aquaculture Systems such as the split-pond systems (Tucker et al. 2014).

Similarly, aquaculture spillovers from R&D in one country benefit another country. For example, R&D and technological developments formulated in Norway have spilled over to the salmon industry in Chile as well as to other fish species (Andersen et al. 2009; Alvial et al. 2012). Labor-saving technologies (automated feeders and video monitors) developed on Norwegian salmon farms have boosted Mediterranean production of sea bream and sea bass. Similarly, fishmeal-sparing efforts in Norwegian feed sector have spilled over to diet formulations in shrimp, tilapia, carp, and other aquaculture species (Chiu et al. 2013). The rapid adoption of white-legged shrimp farming in Asian countries was brought about by technologies developed in the Western hemisphere (Kumar and Engle 2016). Intensive shrimp culture practices such as biofloc technologies are quickly spilling over from US research laboratories to Thailand and from there to other Asian countries (Avnimelech 2009). Biosecurity protocols adopted on Norwegian salmon farms are increasingly followed on Chilean salmon farms to avoid further disease problems (Alvial et al. 2012).

Supply-side Considerations

The nature and degree of competition and readiness of technology supply also influence diffusion of technologies (Stoneman 1991). Competing technology providers foster innovation in the marketplace and lowers production costs, thus encouraging the adoption of cost-saving production methods. However, markets are not always competitive, and the supply of technologies is not elastic (Au and Kauffman 2005). In such cases, innovators focus on their competitors and innovate progressively to maintain a competitive edge.

Rosenberg (1972) proved that initial design flaws of technologies were one of the main reasons for slow diffusion of new technologies. Therefore, technology suppliers have a key role in propagation of technologies through technology improvements, finding alternate uses, development of complementary inputs, and by complementing user skills through training, resulting in the subsequent reduction in costs. Seafood importers play a vital role in the supply chain, enhancing product introduction, promotion (Engle 1997a, 1997b), and innovation (Asche et al. 2007). The greater degree of integration among supply chain members resulted in a shift in US consumption of tilapia products primarily from fresh fillet (exported from Caribbean and Latin American countries) to frozen fillets (exported from South Asia). Innovations in supply-chain auxiliaries (harvest, logistics, and distribution) has tremendously influenced the rapid development of the shrimp, Atlantic salmon, and tilapia industries worldwide (Norman-Lopez and Asche 2008; Asche et al. 2014; Kumar and Engle 2016).

Diffusion of new technologies and R&D have complementary relationships as they stimulate each other (Cohen and Levinthal 1989; Stoneman 1991). Griliches (1998) argued that firms reduce the fate of diminishing returns by developing new products and processes through investments in R&D. Aquaculture industries also combine different technologies and acquire more knowledge and engage actively in R&D within firms or by cooperating with other firms and research organizations. The role of vertically integrated firms such as CP Group (shrimp farming) and Marine Harvest (Atlantic salmon farming) in supplying and promoting productivity-enhancing innovations was vital for the development of these industries. R&D stimulated at US universities, research centers, and independent institutes such as WorldFish Center and AIT have promoted the development of several aquaculture sectors. They often play a lead role in removing technological bottlenecks associated with artificial propagation, selective breeding, disease prevention, and development of suitable rearing systems. Although vaccination has revolutionized the disease management of several high-valued fish species, technology suppliers have a huge role in developing cost-effective and practical mass vaccine-delivery systems (Wise et al. 2015; Peterson et al. 2016). Technologies that improve the functioning of supply-chain auxiliaries (harvest, logistics, and distribution) have contributed to the overall global development of several aquaculture sectors.

Summary and Conclusions

This article summarizes the determinants of technology adoption and the technology dissemination process with respect to global aquaculture development. Shrimp, Atlantic salmon, tilapia, and the US catfish industries have incorporated a wide array of technological advancements along their respective industrial developments. Table 1 summarizes some of the key factors that were found to be vital in the advancement of technologies in major aquaculture industries. Methods used in development of innovations as well as approaches adopted to propagate them are essential components for popularizing aquaculture technologies. Farmers' perceptions of aquaculture technology is a key precondition for its adoption. Technologies that provide greater relative advantage in terms of productivity and costs were found to be favored by producers. The capital- and management-intensive nature of aquaculture seldom allows farmers to switch all their land to a new technology. Hence, technology components should be divisible and their results visible. Compatibility with social and environmental norms, lower degree of complexity, and consistency in results are important technology attributes that aid faster aquaculture dissemination.

Favorable market conditions promote aquaculture technology adoption. Farmers will try to economize the use of the most expensive inputs to optimize their production. Development of nutritionally balanced feeds, better broodstock, selective strains, and increased aeration have enabled the intensive management of more expensive but higher-performance inputs. Availability of complementary technologies from agriculture and other animal husbandry practices has aided the development of several aquaculture technologies.

Size of the farm has been found to be an important farm characteristic that influences aquaculture technology adoption, probably due to the relatively greater financial and management flexibilities associated with larger farms. Availability of high-skilled labor, education, and extension support reduces the complexities associated with aquaculture technology and were found to be critical factors enhancing technology learning. However, sociological factors such as age and experience were found to have a mixed effect on aquaculture adoption.

There is a distinctive difference in the role of institutions in technology diffusion between Asian countries and the US promotion of aquaculture by local and international agencies along with lower regulatory stringency had a significant role in the development of Asian aquaculture. In contrast, stricter regulatory enforcement is hindering the development of aquaculture in countries such as the USA. Regulations intended to minimize environmental externalities alone will not provide economic incentives

TABLE 1. *Factors that had a significant impact on the adoption of some important aquaculture technologies.*

Aquaculture technologies	*Technology characteristics*	*Economic factors*	*Farm characteristics*	*Sociodemographic factors*	*Institutional factors*
Split-pond systems (in the US catfish industry)	System productivity, cost efficiency, control over production	Profitability, financial risk, investment cost	Farm size	Homogeneity	Extension support
Hybrid catfish (in the US catfish industry)	Improved growth, trialability, divisibility, complementarity	Fingerling price, financial risk	–	–	Extension support
Genetically improved farmed tilapia	Control over reproduction, trialability, compatibility, adaptability, divisibility, improved feeds	Spill-overs, cheap labor	Ownership	Age, education	Extension and local government support NGO support
Norwegian Atlantic salmon industry	Genetic gains, vaccination, improved feeds, automation	Offshore labor, higher demand	Farm size	Human capital	Centralized-regulatory environment, private R&D
Asian shrimp industry	Specific pathogen-free broodstocks, hatchery technologies, improved feeds, probiotics	Resource efficiency, higher demand, cheap labor	Farm size	Proximity to supply chain auxiliaries	Feed companies, government support, support from NGO, less stringent regulations

Note: NGO = nongovernmental organization; R&D = research and development.

for adoption. The Norwegian Atlantic salmon industry provides a prime example where policy interventions incorporated incentives for both productivity gains and externality reduction. Hence, technical, environmental, and sociopolitical issues surrounding aquaculture require careful examination upon reviewing the site-specific techno-societal considerations. Such interventions stimulate provision of market innovation and competition.

Although the uncertainties about technologies are high during the initial stages of diffusion, knowledge and information gained by doing so would make this process less uncertain and easier. However, given the wide array of species, production techniques, and the global nature of aquaculture, it is clear that the intensity (level of use of a given technology in any time period) and the extent of adoption (number of technologies being adopted and the number of producers adopting them) depends on the nature of the aquaculture industry and their economic, social, political, and regulatory environments.

Acknowledgments

We wish to acknowledge the review and suggestions on an earlier draft by Drs. Nathan Stone, Suja Aarattuthodiyil, and Matt Griffin. Suggestions and comments provided by the anonymous reviewers also significantly contributed to knowledge base. Errors or omissions are sole responsibilities of the authors.

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