










Technological progress in the US catfish industry

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Abstract

The US catfish industry has undergone significant technological advancements in an attempt to achieve cost efficiencies. This study monitored the progress of the adoption of alternative and complementary technologies in the US catfish industry. A 2019–2020 multi-state in-person survey in Alabama, Arkansas, and Mississippi ($n = 68$), revealed increased adoption of intensively aerated ponds (6,315 ha) and split ponds (1,176 ha). The adoption of alternative, more intensive, production practices has been accompanied by increased adoption of complementary technologies of fixed-paddlewheel aeration, automated oxygen monitors, and hybrid catfish. As a result, the average aeration rate in the tristate region has increased to 7.8 kW/ha with 97% of catfish farms adopting automated oxygen monitors. About 53% of the water surface area in the tristate region was used for hybrid catfish production. Fingerling producers have also adopted a feed-based, oral vaccine against Enteric Septicemia of Catfish, with 83% of the fingerling farms and 73% of the fingerling production area vaccinated against ESC in 2020. Increased adoption of productivity-enhancing technologies in the US catfish industry explains the 59% increase in foodfish productivity from 2010 to 2019.

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Funding information

US Department of Agriculture National Institute of Food and Agriculture, Grant/Award Number: 1013160; Mississippi Agriculture and Forestry Experiment Station Special Research Initiative, Grant/Award Number: 38700; United States Department of Agriculture-National Institute of Food and Agriculture-Southern Regional Aquaculture Center, Grant/Award Number: 2018-38500-28888

Monitoring the progress of adoption of productivity-enhancing technologies will guide researchers and Extension personnel involved in the refinement and dissemination of these technologies.

KEYWORDS

aeration, alternative technologies, catfish industry, complementary technologies, vaccines

1 | INTRODUCTION

Technologies are pragmatic ideas that promote efficient use of limited resources and/or provide ease of management (Rogers, 1983). Innovations such as mechanization, high yielding varieties, irrigation systems, chemical fertilizers, herbicides, and genetically modified organisms provided important impetus to agriculture production (Feder, Just, & Zilberman, 1985; Feder & Umali, 1993; Sunding & Zilberman, 2001) and allowed for the efficient management of capital, land, labor, and time (Mansfield, 1961).

Aquaculture contributes to more than 53% of global aquatic production (FAO, 2020). Greater control over production processes and removal of specific bottlenecks in production has driven adoption of aquaculture technologies (Anderson, 2002; Asche, 2008; Kumar, Engle, & Tucker, 2018). Dissemination of technologies such as hatchery spawning of commercially important species, improved feed and feeding technologies, superior production systems, genetically improved fish strains, and better disease management are some of the key technological advances that have triggered global aquaculture development (Asche, 2008; Asche & Smith, 2018; Dey et al., 2000; Engle, 1989; Kumar & Engle, 2016; Kumar, Engle, & Tucker, 2018).

The catfish industry, the largest US aquaculture segment, has evolved dynamically in response to marketing and production challenges since its inception in the late 1950s (Engle, Hanson, & Kumar, 2021). Competition from lower-priced imports and higher input prices, especially that of feed, have had the greatest impacts on farms in recent times. Lack of control over market prices compelled catfish producers to strive for the development of yield-increasing technologies that provide cost efficiencies. Research studies increasing the carrying capacity and assimilation of fish waste in earthen ponds led to the development of new systems that provided cost efficiencies (Kumar & Engle, 2017; Kumar, Engle, & Tucker, 2016; Tucker, Brune, & Torrans, 2014). Beginning in 2010, catfish farmers began to adopt several alternative, more intensive, production technologies, with the greatest adoption of intensively aerated and split ponds, and limited adoption of in-pond raceway systems. These alternative systems increased the volume of production per unit area on catfish farms (Kumar et al., 2018; Kumar et al., 2021; Kumar, Engle, & Tucker, 2018). Split ponds are modified versions of the partitioned-aquaculture system (Tucker et al., 2014) where existing earthen ponds are divided into a fish-containment basin (15–25% of pond area) and a waste-treatment zone (75–85% of pond area). Water-moving devices such as pumps or large, slow-rotating paddlewheels allow the circulation of oxygenated water from the waste-treatment zone into the fish basin during the daytime, while fixed paddlewheel aerators provide nightly aeration in the fish basin. Intensively aerated ponds are smaller earthen ponds that use aeration rates above 9.3 kW/ha, achieved by the addition of paddlewheel aerators (Kumar & Engle, 2017; Kumar, Engle, et al., 2021). Greater fish yields achieved from these two systems result in cost efficiencies by spreading fixed costs over greater volumes of fish production (Kumar et al., 2018, b; Kumar, Engle, Hegde, & van Senten, 2020).

Split and intensively aerated ponds predominantly use hybrid catfish (♀ channel catfish, *Ictalurus punctatus* × ♂ blue catfish, *Ictalurus furcatus*). Although hybrid catfish have been produced for numerous years (Giudice, 1966), development of mass production hatchery methods in tandem with development of split ponds and intensively aerated ponds (Kumar, Engle, Hanson, et al., 2018), provided opportunities to take advantage of the hybrid catfish performance traits (Gosh et al., 2021). Hybrid catfish grow faster, are better adapted to high stocking densities, consume more feed, have improved feed conversion ratios (FCR), are easier to harvest, and have exhibited tolerance to lower dissolved oxygen (DO) levels (Bosworth, Ott, & Torrains, 2015; Dunham et al., 2000; Kumar et al., 2019).

Widespread adoption of fixed electric paddlewheel aerators is regarded as a key technological development in the US catfish industry (Boyd, 1998; Boyd, Torrains, & Tucker, 2018; Boyd & Tucker, 1998). Prior research showed that fixed electric paddlewheel aerators were more efficient (Boyd, 1998; Boyd et al., 2018; Boyd & Tucker, 1998), economical (Engle, 1989) among various aerator designs, and reduced risks of losses from low DO concentrations (Engle & Hatch, 1988). Recent studies found a steady increase over time in paddlewheel aeration rates on catfish farms (Kumar et al., 2021, b; Kumar & Engle, 2017). Automated oxygen monitoring (AOM) technologies that measure DO and control aerators have facilitated maintenance of DO above 3.0 mg/L (35–40% saturation) (Torrains 2005; Johnson, Engle, & Wagner, 2014; Kumar, 2015; Kumar, Engle, et al., 2021). Producers have increasingly adopted these three complementary technologies (hybrid catfish, paddlewheel aerators, and automated oxygen monitors) despite their high initial investment, primarily due to the ease of management and their contribution to greater yields (Kumar, Engle, et al., 2021).

Enteric Septicemia of Catfish (ESC) is a prominent bacterial disease, predominantly affecting catfish fingerlings. Efforts to develop effective vaccines against ESC were hindered by the inability to administer vaccines to immunocompetent fish raised in large earthen ponds. Recent development of an ESC-vaccination platform (Wise, Greenway, & Byars, 2015) has allowed for the measured delivery of an effective live attenuated vaccine (Aarattuthodiyil et al., 2020; Greenway et al., 2017; Griffin et al., 2020) to immunocompetent fingerlings in commercial pond settings. This one-time, feed-based vaccination protocol has been proven economical in controlling ESC in both channel and hybrid catfish under commercial fingerling production settings (Kumar et al., 2019; Wise et al., 2020). Its use on catfish fingerling farms has increased since it became available commercially in 2018.

In the context of this article, split and intensively aerated ponds are together defined as intensive-alternative production technologies, whereas complementary technologies include hybrid catfish, paddlewheel aeration, automated oxygen monitors, and ESC vaccination. Both alternative production technologies and complementary technologies are collectively termed productivity-enhancing technologies.

Given the magnitude of these technological developments in the US catfish industry (Figure 1), monitoring the progress of adoption is necessary for researchers and policymakers to understand the dynamics of the industry and to refine and propagate ongoing improvements. Intensity and extent of technology adoption are distinct measures in the technology adoption literature. Intensity of adoption measures the level of use of a given technology over any period (area under or number of adopters using a technology at a given time). Extent of adoption refers to the variety of technologies adopted in a sector, often measured in terms of area under or number of adopters using different technologies.

The objectives of this study were to monitor the progress of the adoption of alternative-production technologies as well as determine the current status of adoption of complementary technologies in the US catfish industry. Specific objectives involve:

1. Alternative-production technologies: Monitoring adoption rate of intensively aerated ponds and split-pond systems from 2010 to 2019.
2. Complementary technologies: Estimating the current status (2019) of the use of paddlewheel aeration, AOM systems, and hybrid catfish fingerlings in the US catfish industry,
3. Monitoring the progress of the adoption of ESC vaccination from 2013 to 2020 on fingerling producing farms.

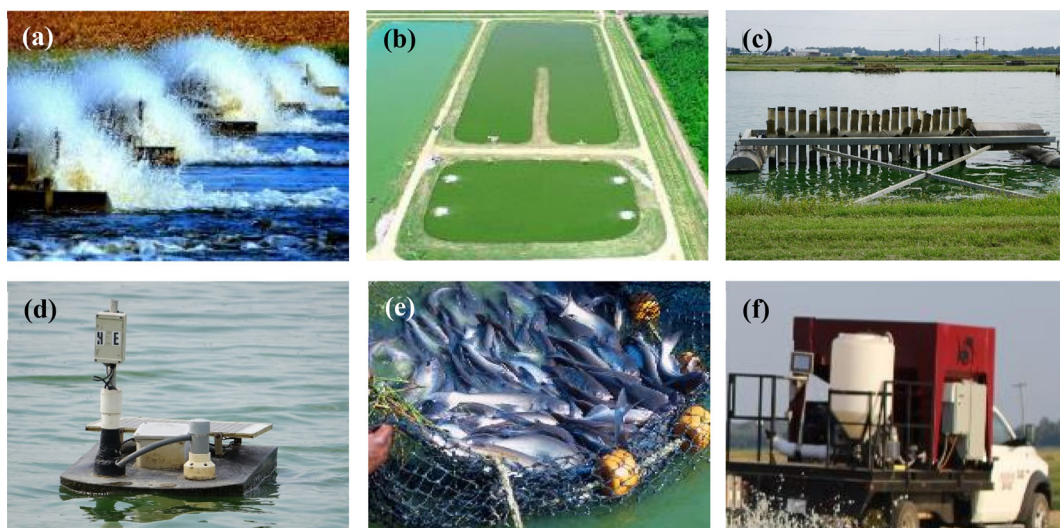


FIGURE 1 Productivity-enhancing technologies in the catfish industry (a) intensively aerated ponds, (b) split ponds, (c) electric paddlewheel aerator, (d) automated oxygen monitors, (e) hybrid catfish, and (f) ESC vaccination platform. Photo credits: (a) Les Torrains, USDA-ARS; (b) Danny Oberle, USDA-ARS; (f) Kenner Patton, MSU

2 | METHODS

2.1 | Survey and data collection

A survey of catfish farms was conducted during 2019–2020 to monitor the progress of adoption of alternative and complementary catfish production technologies. The in-person survey was designed as a census of all catfish farms (catfish hatcheries and foodfish farms) in the tristate region of Alabama, Arkansas, and Mississippi. The tristate region accounted for over 93% of the US catfish production volume (158 million kg) and 90% of the US catfish production area (22,720 ha) in 2019. Extension specialists in respective states sent out a notice of the survey to catfish farmers with available mailing addresses, followed by telephone calls requesting personal interviews. USDA Census of Aquaculture 2018 (USDA-NASS, 2018) provided insights into the number of farms existing in the tristate region. Of the 291 farms listed in the tristate region, 68 farms participated in the survey and provided complete responses, a participation rate of 23% (Table 1). The survey covered 15,045 ha, a 66% coverage rate of the total production area. Figure 2 illustrates the geographical spread of the catfish farms surveyed in the tristate region.

The survey instrument of catfish farms captured the acreage in catfish production with traditional and alternative-production systems. Adopters—producers who had adopted at least one of two alternative-catfish production systems (split ponds and/or intensively aerated ponds)—were asked to specify the area under production for each production system. Information on stocking practices (single batch, multiple batch, or modular type¹), average farm aeration rate (kW/ha), average stocking density (nos./ha), average feeding rate (MT/ha), and FCRs were also requested. In addition, respondents were asked for information on farm size, specific aeration rates under different farming practices, areas under complementary technologies such as hybrid catfish fingerlings, and whether they had adopted AOM systems.

Fingerling producers were also surveyed with respect to the production of hybrid catfish. The fingerling survey covered 95% of the fingerling production area and 83% of the fingerling producers (Table 1). Producers were also asked whether they had vaccinated their fingerlings against ESC. Additional information was requested on the

TABLE 1 Details of the 2019 survey of the US catfish industry

Industry components	List frame	Completed	Rate (%)
Catfish farms			
Number of responses	291	68	23%
Area coverage (ha)	22,720	15,045	66%
Fingerling farms (hatcheries)			
Number of responses	12	10	83%
Area coverage (ha)	2,980	2,841	95%
Foodfish farms			
Number of responses	279	66	24%
Area coverage (ha)	19,740	12,204	62%
Processing plants			
Processing plants, number	9	8	89%
Total processed volume (million kg)	76.7	69.7	91%

Note: Number of fingerling and foodfish farms do not add to total numbers as some farms can produce both products.



FIGURE 2 Tristate map indicating the geographical location of the catfish farms surveyed in Alabama, Arkansas, and Mississippi

fingerling production area receiving vaccination each year from 2013 (when commercial trials began) to 2020. Data on the number of ponds and areas receiving the vaccine on each fingerling farm were collected from the farm veterinarian overseeing the vaccination program.

TABLE 2 Average values of key production parameters and farm parameters on US catfish farms in the tristate region, 2019

Parameters	Units	Mean ± SD
Stocking density ^a	(no./ha/yr)	22,948 ± 4,435
FCR ^a	(ratio)	2.4 ± 0.26
Feeding rate ^a	(MT/ha/yr)	20.4 ± 6.4
Percentage of farms following different management practices		
Multiple batch ^b	(%)	79%
Single batch ^b	(%)	59%
Modular three-stage systems ^b	(%)	9%
Farm size		
Alabama	(ha)	181 ± 194
Arkansas	(ha)	102 ± 58
Mississippi	(ha)	296 ± 389
Foodfish farm	(ha)	184 ± 293
Fingerling farm	(ha)	284 ± 106
Tristate farm average	(ha)	221 ± 356

^aStocking density, FCR, and feeding rate were reported only from farms that generate revenue primarily from sales of foodfish ($n = 60$). The above parameters were found to be different on fingerling operations and not disclosed to preserve confidentiality. Reported FCR values are farm-level measures, calculated as total feed fed divided by total harvested weight, not on a dry-matter basis.

^bEvents are not mutually exclusive as farms adopt multiple cropping strategies at any given time.

Processing plants were surveyed to request information on the percentage of the total round weight of catfish processed in 2019 that were hybrids (Table 1). The study covered 89% of the processing plants ($n = 9$) in the tristate region.

2.2 | Accounting for nonparticipating farms

Estimating the industrywide adoption of technologies requires accounting for farms that did not participate in the survey. These nonparticipating farms ($n = 223$) were found to be smaller, ranging in size from 23 to 37 ha (USDA-NASS, 2018; USDA-NASS, 2020). To account for nonresponses, average values of the area under production for each technology reported by respondents were calculated within geographic regions (Southwest Arkansas, Delta region of Arkansas, Northeast Arkansas, Delta region of Mississippi, East Mississippi, and West Alabama). These regional averages were then used to estimate the area under production for each technology. Data from this survey were graphed along with that of a pre-2013 survey (Kumar, 2015; Kumar, Engle, et al., 2021) to identify trends of technological progress across the catfish industry.

3 | RESULTS

Key production parameters of catfish farms are shown in Table 2. The average stocking density, feeding rate, and FCR on catfish farms were 22,948 fish/ha, 20.4 tons/ha, and 2.4, respectively. Seventy-nine percent of the survey respondents followed multiple-batch cropping systems, 59% single-batch, and only 9% used a three-phase modular

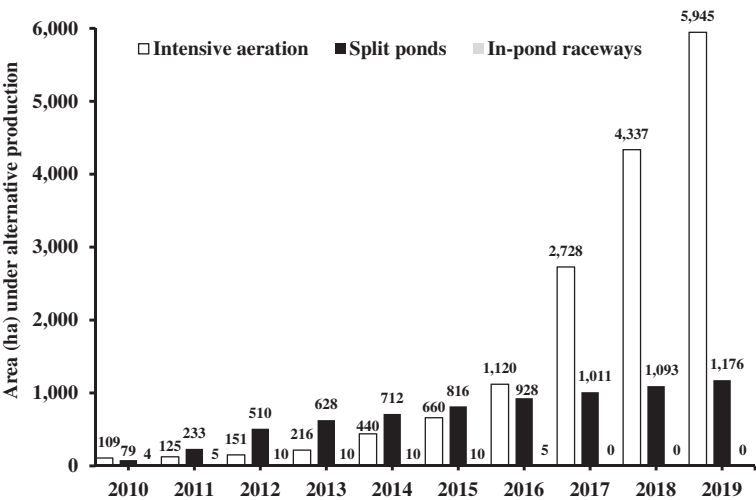


FIGURE 3 Area under various alternative catfish production technologies in the tristate region, 2010–2019

TABLE 3 Adoption of alternative catfish production technologies in the catfish industry, 2019

Regions	Intensively aerated ponds		Split ponds		Alternative systems	
	Area (ha)	Adopters (nos.)	Area (ha)	Adopters (nos.)	Area (ha)	Adopters (nos.)
Alabama	1,588	22	13	1	1,601	23
Arkansas	254	6	115	3	369	6
Mississippi	4,102	61	1,048	13	5,150	67
Tristate total	5,945	89	1,176	17	7,121	96

Note: The values are adjusted for adoption in nonparticipating areas in Alabama, Arkansas, and Mississippi.

farming system. The average size of catfish farms across the tristate region was 221 ha, with state average areas of 181, 102, and 296 ha in Alabama, Arkansas, and Mississippi, respectively. The average sizes of foodfish and fingerling producing farms were 184 and 284 ha, respectively (Table 2).

The industry survey revealed important information on trends in the adoption of alternative catfish production technologies. Adoption of two of the three alternative technologies (split ponds, intensively aerated ponds) showed an increasing trend (Figure 3). As of 2019, there were 96 adopters, 31% of which (89 farms) had adopted intensive aeration (Table 3). By state, 61, 22, and 6 farms had adopted intensive aeration in Mississippi, Alabama, and Arkansas, respectively. The corresponding share of areas under intensive aeration was (71%) in Mississippi, 25% in Alabama, and 4% in Arkansas. Split ponds were adopted on 17 catfish farms, 6% of catfish farms (Table 3), with 13 farms in Mississippi, 3 in Arkansas, and 1 in Alabama as of 2019. The majority (89%) of the area in split ponds was in Mississippi (1,176 ha), followed by 115 ha in Arkansas (Table 3). Ten producers (10% of 96 farms) had adopted both intensively aerated and split ponds on their farms. The area under intensive-aeration systems (> 9.3 kW/ha) has exceeded that of split ponds since 2016. In-pond raceways, previously used for catfish production during 2010–2016, were no longer in use for catfish production in 2019.

The survey also revealed that nearly 40% of the foodfish production area in the tristate region had adopted alternative-production systems with the majority adopting intensively aerated ponds (Figure 4). Over the last 10 years (2010–2019), intensively aerated ponds were adopted at an annual rate of 595 ha/year (3%/year) while split ponds were adopted at an annual rate of 118 ha/year (0.6%/year).

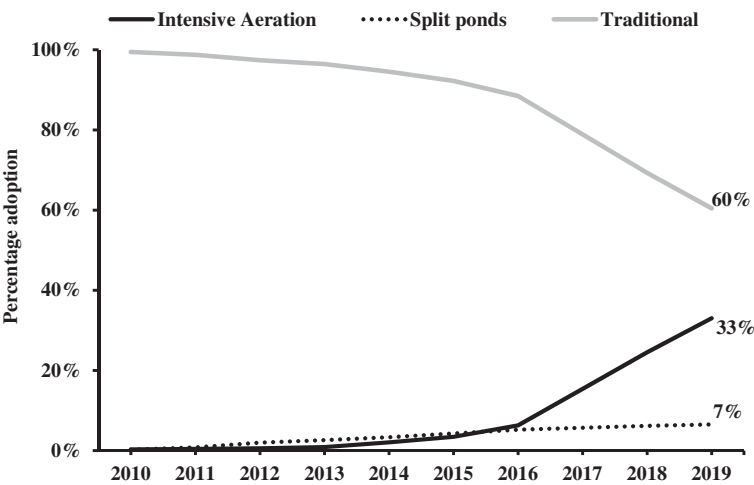


FIGURE 4 Trends in adoption of various foodfish production practices in the US catfish industry, 2010–2019

TABLE 4 Comparison of production parameters (Mean \pm SD) among adopters and nonadopters of alternative catfish production technologies, 2019.

Parameters ¹	Adopters of alternative production technologies	Nonadopters of alternative production technologies	p-value
Number of observations (n)	34	26	-
Stocking density (no./ha)	22,234 \pm 3,050	17,512 \pm 4,580	0.000
Aeration rate (kw/ha)	8.38 \pm 3.13 ^a	8.16 \pm 1.66 ^b	0.000
FCR (ratio)	2.20 \pm 0.28	2.13 \pm 0.24	0.252
Feeding rate (MT/ha)	22.92 \pm 6.80 ^a	17.20 \pm 3.94 ^b	0.000
Yield (kg/ha)	10,973 \pm 2,782 ^a	8,621 \pm 2,245 ^b	0.001

Note: Values with different superscripts within each row indicate significant statistical differences as identified by a Student's *t*-test.
¹Production parameters were reported only from farms that generate revenue primarily from sales of foodfish (*n* = 60). The above parameters were different on fingerling operations and not disclosed to preserve confidentiality. Reported FCR values are farm-level measures, calculated as total feed fed divided by total harvested weight, not on a dry-matter basis.

Production parameters such as stocking density, aeration rate, feeding rates, and fish yield were significantly higher (*p* < 0.05) on farms that had adopted alternative technologies (*n* = 34) relative to farms that continued to use traditional farming strategies (*n* = 26). However, FCR was not significantly different among farms adopting alternative catfish production technologies and those that had not (Table 4).

The use of fixed paddlewheel aeration was found to have increased as a result of the intensification of production in split ponds and intensively aerated ponds. The weighted average² paddlewheel aeration rates in Alabama, Arkansas, and Mississippi were found to be 7.4, 6.9, and 8.3 kW/ha, respectively, resulting in an industry weighted average aeration rate of 7.8 kW/ha (Figure 5). The increased adoption of alternative catfish production systems has been accompanied by increases in complementary technologies of AOM and hybrid catfish. Survey results showed that 97% of catfish farms (and all adopters of alternative-production technologies) had adopted AOM systems, and 53% of the production area was in hybrid catfish production in 2019 (Table 5). For hybrid catfish production, the greatest adoption rate was in Mississippi (69%), followed by Arkansas (32%) and Alabama (24%). Cross tabulations of results also showed that over 59% of the surveyed farms in 2019 have adopted hybrid catfish on their farms. Almost

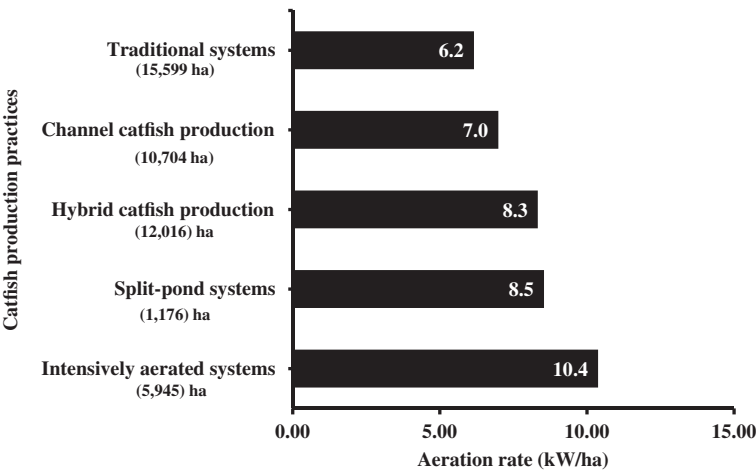


FIGURE 5 Weighted average aeration rate (kW/ha) of various production practices in the US catfish industry, 2019. Numbers in parenthesis represent the corresponding area of adoption, after adjusting for nonparticipants

TABLE 5 Area and percentage share of the farming area in hybrid and channel catfish production in the tristate region, 2019

Regions	Hybrid catfish		Channel catfish	
	(ha) ^a	(% share of area)	(ha) ^a	(% share of area)
Alabama	1,635	24%	5,085	76%
Arkansas	551	32%	1,169	68%
Mississippi	9,830	69%	4,450	31%
Tristate total	12,016	53%	10,704	47%

Note: The values are adjusted for adoption of hybrids and channel catfish in nonparticipating areas in Alabama, Arkansas, and Mississippi.

^aArea includes foodfish and fingerling production.

TABLE 6 Adoption of complementary technologies among adopters and nonadopters of alternative catfish production technologies (*n* = 68)

Area under	Intensively aerated pond systems	Split-pond systems	Traditional systems
Hybrid catfish (%)	68%	100%	40%
Channel catfish (%)	32%	0%	60%
Average aeration rate (kW/ha)	10.4	8.5	6.2
Automated oxygen monitor (%)	100%	100%	94%

35% of the adopters of alternative production systems (13 farms) have exclusively adopted hybrids on their farms. Of farms that adopted hybrid catfish, 29% (20 farms) grow hybrid catfish exclusively. All adopters of split-pond systems used only hybrid catfish. The adoption of complementary technologies among adopters of alternative technologies are provided in Table 6. The survey of fingerling producers found that 60% of the catfish fingerlings produced in the industry were hybrid catfish (Table 7). An alternative metric of adoption of hybrid catfish obtained from the

TABLE 7 Share of hybrid and channel catfish based on the number of fingerlings produced and volume of fish processed in 2019. Values in parenthesis represent respective shares

Industry metrics	Hybrid catfish	Channel catfish
Fingerlings produced in catfish hatcheries (million fingerlings)	315 (60%)	209 (40%)
Roundweight processed in catfish processing plants (million kg)	85 (58%)	62 (42%)

TABLE 8 Comparison of production parameters (Mean \pm SD) among exclusive adopters and nonadopters of hybrid catfish, 2019. Values with different superscripts within each row indicate significant statistical differences as identified by a Student's *t*-test

Parameters	Exclusive adopters of hybrid catfish	Exclusive nonadopters of hybrid catfish	<i>p</i> -value
Number of observations (<i>n</i>)	16	24	-
Stocking density (no./ha)	21,490 \pm 5,338	19,063 \pm 4,641	0.149
Aeration rate (kW/ha)	8.41 \pm 3.91	8.32 \pm 3.06	0.118
FCR (ratio) ^a	2.29 \pm 0.34	2.20 \pm 0.22	0.371
Feeding rate (MT/ha)	24.49 \pm 7.95 ^a	18.03 \pm 5.64 ^b	0.009
Yield (kg/ha)	10,956 \pm 3,585 ^a	8,961 \pm 2,504 ^b	0.065

^aReported FCR values are farm-level measures of feeding efficiency, calculated as total feed fed divided by total harvested weight, not on a dry-matter basis.

survey of catfish processing plants suggested 58% of the roundweight processed (2019) in the industry was hybrid catfish (Table 7). All three measurements found increased adoption of hybrid catfish in the industry with adoption ranging from 53 to 60% depending on the metrics.

Adopters of hybrid catfish were engaged in relatively more intensive production practices on their farms (Table 8). Feeding rates were found to be significantly higher ($p < 0.05$) on farms exclusively raising hybrid catfish ($n = 16$) relative to the farms exclusively raising channel catfish ($n = 24$). Yield was also found significantly higher for adopters of hybrids over channels, but at 10% level of significance ($p < 0.07$).

Technological progress in disease management was also found on US catfish farms. About 1,379 ha, or 73% of the fingerling production area, had adopted the use of the ESC vaccine for disease management in 2020 (Figure 6). Ten of the 12 (83%) catfish fingerling producers had used various degrees of vaccination on their fingerling production area in 2020.

4 | DISCUSSION

Adoption of new technologies developed through research and development has played a key role in the evolution of aquaculture. Aquaculture technologies aid in increasing farm productivity and supply, reducing the cost of production, improving resource-use efficiency, and generating greater employment, thus resulting in the overall development of the sector and local economies (Brugere, Padmakumar, Leschen, & Tocher, 2021; Kumar, Engle, & Tucker, 2018).

Although uncertainties about technologies are high during the initial stages of diffusion, dissemination of research knowledge related to the new technologies reduce uncertainties. However, the intensity (level of use of a given technology over any period) and the extent of adoption (number of technologies and adopters) depend on the nature of the industry and the economic, social, political, and regulatory environments (Rogers, 2003). In the catfish

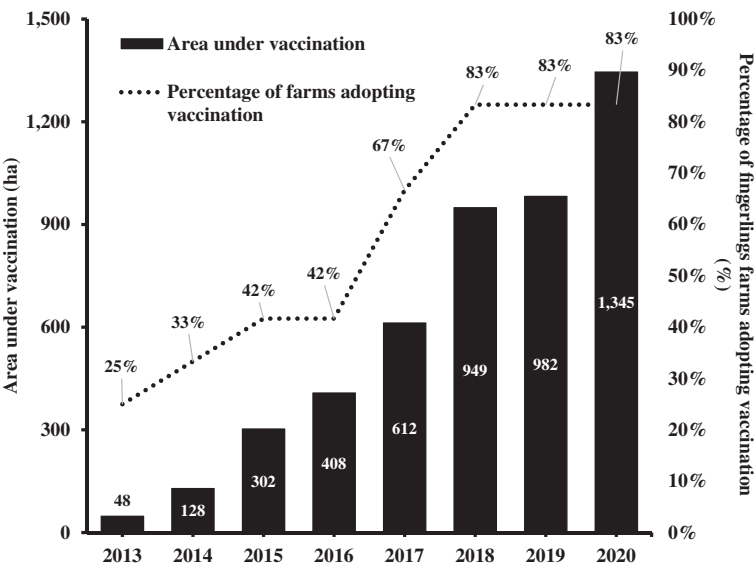


FIGURE 6 Fingerling area under ESC vaccination program in the tristate region and the percentage of farms adopting ESC vaccination ($n = 12$), 2013–2020

industry, the contraction period (2003–2013) likely triggered renewed interest in production technologies that are more cost-efficient (Engle, Hanson, & Kumar, 2021).

Increased attention to improving resource use and reducing negative environmental impacts of food production have prompted greater attention to environmental sustainability and performance of aquaculture (Boyd et al., 2017; Boyd et al., 2018; Engle et al., 2017). Based on shrimp farming data from Thailand and India, results showed that intensification of production resulted in more efficient use of resources (land, water, labor, management, energy, and capital). In the United States, a similar study comparing resource-use efficiency across species and production systems showed that intensification improves resource use, but is also more economically efficient (Engle, Kumar, & van Senten, 2021). Thus, intensive systems that produce more output per unit of resource use are more sustainable from both environmental and economic perspectives.

Kumar (2015) found increasing adoption of intensively aerated and split ponds from 2010 to 2013 period. Increased productivity and greater control over production were cited as the primary factors for adoption. Deterrents to adoption were reported to be high initial investment cost and increased financial risk. Adoption of new production systems was also accompanied by adoption of the complementary inputs of hybrid catfish and automated oxygen monitors (Kumar, Engle, et al., 2021). Complementary technologies can reduce uncertainty and inefficiencies in the initial phase of technology adoption (Mansfield, 1961; Rogers, 1983) and may have facilitated the rate of adoption in the catfish industry.

Intensively aerated ponds emerged in this study as the most widely adopted technology, with the area under intensive aeration surpassing that of split ponds. The relative ease of adoption and reduced initial capital investment likely facilitated this growth among more risk-averse early-majority and late-majority adopters (Rogers, 2003). The ready availability of used paddlewheel aerators at reduced cost likely facilitated adoption of increased aeration rates as compared to split ponds. Reduced investment costs, as well as the ease of adoption of increased aeration, were principal reasons for greater adoption rates (Kumar, Engle, et al., 2021). Overall, aeration rates have tripled from 1982 to 2010 (Figure 7), with the average aeration rate increasing by 66% from 2010 to 2019.

Adoption of split ponds has occurred mostly in Mississippi and Arkansas and not Alabama, likely because the watershed ponds in West Alabama are not conducive to construction of split ponds. Moreover, the less expensive

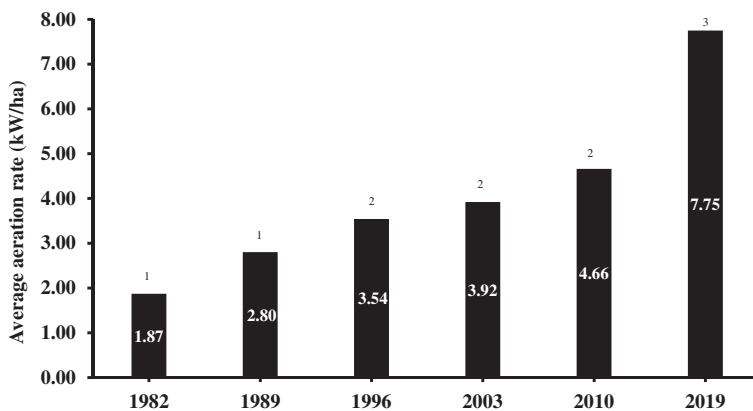


FIGURE 7 Trends of average paddle-wheel aeration rate in the catfish industry, 1982–2019. Source: ¹Boyd (1998); ²USDA (2010); ³current study

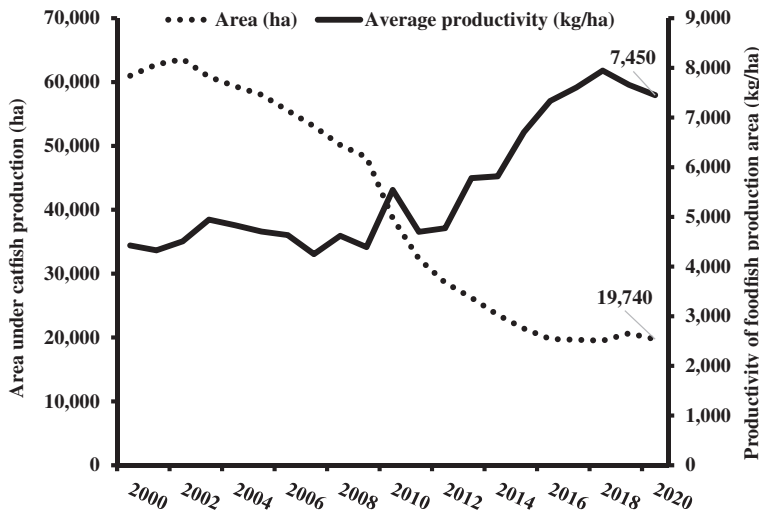


FIGURE 8 Trends in the area under foodfish production and productivity in the US catfish industry, 2000–2020

electric rates in East Mississippi and West Alabama may have facilitated greater adoption of intensive aeration in these two regions.

Land productivity in the catfish industry has increased by 59% (Figure 8) over the last 10 years (Hanson, 2020; USDA-NASS, 2020). The adoption of intensively aerated ponds and split ponds is considered the primary reason for the recent increase in productivity in the US catfish industry (Kumar, Engle, & Tucker, 2018). For example, productivity has increased by 30% between 2013 and 2019 (Table 9), the same period over which adoption of intensively aerated and split ponds increased by 1,229% and 76%, respectively. In-pond raceways were no longer in use in 2019, due to the high initial investment, high annual fixed cost, and lack of profitability (Roy and Brown, 2016; Kumar, Engle, Hanson, et al., 2018).

A comparison of the current study with Kumar (2015) found that the adoption of hybrids has more than doubled (140%) since 2013 (Table 9). A greater supply of hybrid catfish fingerlings and superior performance of these fish in intensive systems has been central to the adoption of hybrid catfish in the US catfish industry. The intensity of adoption of hybrid catfish was found higher among larger integrated farms that raise them in single-batch crops. Channel

TABLE 9 Comparative adoption of productivity-enhancing technologies in the US catfish industry

Regions	Area under			Average	
	Intensive aeration	Split ponds	Hybrid catfish	Aeration rate*	Foodfish yield*
	(ha)	(ha)	(ha)	(kW/ha)	(kg/ha)
Tristate in 2013 ^a	475	670	~5,000	5.3	5,850
Tristate in 2019 ^b	6,315	1,176	12,016	7.8	7,621
Percentage change	1,229%	76%	~140%	47%	30%

Note: The 2019 study values are adjusted for adoption in nonparticipating areas in the tristate region.

*Weighted averages.

Source: ^a Kumar (2015); ^b Current study.

catfish, however, is still an important component of the catfish industry. About 79% of the farms were found to continue to stock channel catfish with 41% of respondents raising them exclusively. More specifically, 48% of the non-adopters of alternative-production systems exclusively produced channel catfish. Channel catfish are mostly raised in multiple-batch systems and harvested using grading socks wherein fish are held overnight to allow grading of small fish back into the pond for further growth till they reach market size. Continuous production and partial harvests supplement the year-round supply of fish to the markets. Relative to channel catfish, hybrid catfish have a smaller head-to-trunk ratio resulting in their entanglement in the sock graders, rendering grading an unsuitable harvesting strategy for hybrid catfish production (Hanson et al., 2020; Kumar, Li, et al., 2019; Kumar, Wise, et al., 2021). Therefore, most producers raise hybrid catfish in single-batch systems with fish harvested completely at the end of the growing season (October–January). Such seasonality of supply creates oversupply of fish in the fall and under-supply the rest of the year. Hybrid catfish production is more capital and management intensive (Kumar et al., 2020) because of expensive fingerlings (~67% more expensive than channel catfish fingerlings; Kumar & Engle, 2011, 2014; Engle, Kumar, & Bouras, 2010), and higher stocking, feeding, and aeration rates. As a result, there are producers who continue to rely on channel catfish stocked in multiple-batch systems to supply processing plants when hybrid catfish are not available.

Vaccination of fish against specific diseases has been an effective disease management tool for Norwegian Atlantic salmon farms (Asche, Roll, & Tveterås, 2008; Kumar & Engle, 2016), tilapia farms in Brazil, China, and West Africa (Bergesen & Tveterås, 2019), and European seabass (Miccoli, Manni, Picchietti, & Scapigliati, 2021). The development of the ESC vaccine along with its effective delivery to immunocompetent catfish fingerlings has allowed for better survival of both channel catfish and hybrid catfish fingerlings on commercial catfish farms (Kumar, Byars, et al., 2019; Kumar, Li, et al., 2019). Recent studies suggested that the ESC vaccine also offers cross protection against *E. piscicida* (Griffin et al., 2020; López-Porras et al., 2021), an emerging disease in hybrid catfish (Griffin et al., 2019; Reichley et al., 2018). Since the inception of this ESC vaccination program in 2013, ~1.5 billion catfish fingerlings have been vaccinated. The increased adoption of commercial ESC vaccination in terms of the number of adopters as well as the area under vaccination is an example of private–public collaboration and research and Extension support for the US catfish industry.

The environmental performance of food production is increasingly understood to be an important consideration (Gephart et al., 2021; Naylor et al., 2021; Tucker et al., 2014). While outside the scope of this article, understanding which technological advances have been adopted on farms provides insight into potential effects on environmental performance. For example, a number of recent studies have suggested that intensive production practices are more efficient in their use of key resources (Boyd et al., 2017; Boyd, Tucker, McNevin, Bostick, & Clay, 2007; Engle et al., 2017; Chatvijitkul, Boyd, Davis, & McNevin, 2017; Tucker et al., 2017; Boyd et al., 2020; Davis, Boyd, & Davis, 2021). Thus, the intensification of catfish production found in this study would be expected to enhance the environmental performance of catfish production. A 2021 study reported a high level of efficiency in the new, more

intensive catfish production methods in the use of resources such as land, labor, capital, management, energy, and water (Engle, Hanson, & Kumar, 2021; Engle, Kumar, & van Senten, 2021).

The efficiency of use of feed is an important component of environmental performance. Pond production of catfish tends to have higher FCRs relative to species such as salmonids. This study found average FCRs of 2.2 for adopters of new technology and 2.1 for nonadopters, with no significant difference. Yet catfish research studies have reported FCRs for catfish to range from 1.2 to 1.8 in the fingerling production stage and 1.5 to 2.2 in the foodfish production stage (Li & Robinson, 2008; Robinson & Li, 2020). Several reasons may explain these differences. First, production results on commercial farms often differ from those on research facilities (Engle, 2007; Kaliba & Engle, 2005). Second, US catfish ponds have high hydraulic retention periods (10 to 15 years) and fish that learn to escape the harvest nets tend to grow large with poorer FCRs. The lack of frequent pond draining makes it difficult to calculate an accurate FCR from commercial catfish ponds. Year-round supply of fish to processing plants often means carrying large inventories of submarket-sized fish over production seasons. Off-flavor catfish may take months to purge and be marketable, further contributing to poor FCR because they must be held within marketable size ranges. In addition, fish that are lost to avian predators further contribute to higher FCRs (Engle et al., 2020). Other studies have shown that catfish production in single-batch systems achieve lower FCRs as compared to multiple batch systems (Engle et al., 2020; Hanson et al., 2020; Kumar et al., 2020). This study showed increased adoption of single-batch systems on US catfish farms that are indicative of progress toward more resource-efficient and environmentally sustainable production performance. Nevertheless, further improvements in FCR are needed.

5 | CONCLUSIONS

This study quantified trends in the adoption of productivity-enhancing technologies in the US catfish industry and found an increasing intensification of culture practices. Intensively aerated ponds and split ponds have been increasingly adopted by the catfish industry. Over one-third of the foodfish production area had adopted alternative catfish production systems by 2019. The advent of these intensive systems has been accompanied by increased adoption of complementary technologies such as hybrid catfish fingerlings, increased fixed-paddlewheel aeration, and oxygen-monitoring systems on farms. Hybrid catfish were raised on 53% of the farmed area while the average paddlewheel aeration rate has risen to 7.8 kW/ha. AOM systems were in use on the vast majority of farms surveyed to manage DO with automated control of paddlewheel aerators based on measurements of DO on the vast majority of the surveyed farms. The study also found that vaccination against ESC had been adopted on more than 83% of fingerling production farms. Progressive adoption of production-enhancing alternative and complementary technologies was found to be central to the increase in productivity on US catfish farms. Findings from this study are valuable to policymakers, Extension specialists, and researchers working with the US catfish industry and allied US aquaculture industries, as well as to catfish producers.

ACKNOWLEDGMENTS

We sincerely thank all the catfish producers and processors from the states of Alabama, Arkansas, and Mississippi who provided us with their responses. We also thank the United States Department of Agriculture-National Institute of Food and Agriculture-Southern Regional Aquaculture Center (USDA-NIFA-SRAC Grant No. 2018-38500-28888) for funding this research along with support from the Mississippi Agriculture and Forestry Experiment Station Special Research Initiative (MAFES-SRI-Grant #38700) and the US Department of Agriculture National Institute of Food and Agriculture (USDA-NIFA Hatch Project Accession Number 1013160).

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ENDNOTES

- ¹ Modular systems—often called a three phase system—involves three distinct phases of production. The first phase involves raising of catfish fry to fingerlings (30–114 g). The second phase involves growing fingerlings to stockers (114–270 g), and the final phase of production involves the growout of stockers to market size fish (>567 g).
- ² Weighted average paddlewheel aeration rates = (Sum product of aeration rate specifically followed in specific culture strategies and area under each strategies) ÷ (the total area).

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How to cite this article: Hegde, S., Kumar, G., Engle, C., Hanson, T., Roy, L. A., Cheatham, M., Avery, J., Aarattuthodiyil, S., van Senten, J., Johnson, J., Wise, D., Dahl, S., Dorman, L., & Peterman, M. (2022). Technological progress in the US catfish industry. *Journal of the World Aquaculture Society*, 53(2), 367–383. <https://doi.org/10.1111/jwas.12877>