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Effect of Substrate Type and Fish Activity on Freshwater Meiofaunal Colonization

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Abstract

THE CONTEXT**.** Meiofauna are a natural food source for higher aquatic organisms. However, their colonization (abundance and biomass) response to substrate type and perturbation needs to be explored. **Aims.** The study investigated how meiofaunal colonization (MC) was affected by substrate type (organic and inorganic as artificial substrates (AS), and natural sediment as a control) and ascending fish activity (FA), representing disturbance. **Methods.** This study was divided into three two-month periods depicting (FA) escalation between November 2021 and April 2022. Nine replicates of organic and inorganic substrates were positioned at the beginning of each period and recollected after a two-week colonization period, plus nine more replicates of the natural sediment cores. Environmental variables were evaluated. **Key results.** Despite the insignificant difference between the (AS) in terms of (MC), it significantly differed from that of the natural substrate within each period. However, (MC) significantly differed among the three (FA) periods, except for those of the natural substrate. Furthermore, the third (FA) had the lowest (MC) for all substrates. **Conclusions.** (MC) in (AS) protected from fish predation and/or disturbance, enhancing meiofaunal proliferation and mucus secretion, creating diverse micro-niches promoting colonization. **Implications**. Meiofaunal proliferation may enhance the fish nutrition sustainability in aquaculture. However, further research is needed to optimize this strategy.

Keywords: Abundance, Activity, Biomass, Meiofaunal-colonization, Substrate.

Introduction

Meiofauna are a diverse group of microscopic invertebrates inhabiting aquatic sediments that pass through a 500 µm sieve but are retained on a 44 µm sieve [1]. Meiofauna are essential for many vital processes, including nutrient cycling and bioturbation (mixing sediments and increasing oxygenation) [2]. Additionally, meiofauna facilitate the flow of nutrients by breaking down organic molecules [3].

Artificial substrates are man-made materials designed to mimic the properties of natural substrate, providing a foundation for the growth and development of various organisms, including meiofauna. They are transplanted on the water–sediment interface primarily to neutralize the effect of natural sediment variability on the benthos [4]. These substrates find applications in diverse fields, including habitat enhancement [5], conservation [6], and bioremediation [7], environmental monitoring [8], restoration [9], and aquaculture [10].

Exploring the effects of artificial substrates' characteristics on meiofaunal colonization may elucidate the documented positive outcomes of cultured organisms. Artificial substrates promote culture conditions by 1) reducing ammonia and nitrite concentrations in farming water [11,12]; 2) providing sustainable natural healthy live food to cultured organisms [13] and [14]; 3) increasing the growth and feed efficiency of cultured organisms [15]; and 4) reducing the relative stocking density being cultured by increasing the surface area of the culturing tank, which in turn reduces stress levels (competition for space and negative behavioral interactions, such as cannibalism) [16].

Many factors may influence meiofaunal settlement and colonization of artificial substrates. Specifically, designed structures of artificial substrates for research (e.g., colonization plates, settlement panels) represent the experimental setups [17]. Similarly, artificial reefs, breakwaters, and aquaculture structures represent constructed habitats. Furthermore, the use of different materials, such as

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wood, macrophytes, and leaf litter [18], plastic [19], and ceramic [20], as artificial substrates has produced inconsistent results.

Zeppilli et al. [21] studied nematode colonization on organic and inorganic substrates deployed in the deep sea. They reported differential nematode responses to inorganic and organic substrates. Near hydrothermal vents, nematodes prefer inorganic substrate, whereas they prefer organic substrate in areas not influenced by vent activity. Furthermore, nematodes colonized inorganic substrate earlier than organic substrate. However, organic and inorganic substrates have not been adequately studied. Likewise, other factors, such as the presence of high fish density with gradually increasing activity, have not been identified.

The fish–meiofauna predation relationship has been documented by Spieth et al. [22], Weber and Traunspurger [23], Weber and Traunspurger [24], Weber and Traunspurger [25], and Weber and Traunspurger [26], who highlighted benthic nematode predation by fish larval stages. However, Abada et al. [27] reported that benthic nematode predation is not exclusively restricted to the fish larval stages.

The present study aimed to address the entire meiofaunal community colonization response (represented by abundance and biomass) to the interaction of the artificial substrate type (AS) (inorganic/organic) and the progressive–fish activity (FA). To investigate this interaction, this study utilized two compatible woven materials justified by the natural sediment substrate. The first material is polyethylene (plastic pan scourer) as an inorganic substrate. The second is *Luffa aegyptiaca* (of similar dimensions), as an organic substrate. This approach ensures the standardization of substrates. The study will proceed through the objectives outlined below:

1. Does the type of AS (inorganic/organic) affect meiofaunal colonization differently?

2. Is meiofaunal colonization (MC) in the (AS) consistent over the (FA) periods?

Material and Methods

Ethics statement

Ethical approval was obtained from the KFS-IACUC ethical committee at Kafrelsheikh University, Egypt (Approval number: IACUC: KFS-IACUC/199/2024).

Study area

A tilapia earthen pond in Kafr Elsheikh Governorate, Northern Nile Delta, Egypt (31° 22’ 26” to 31° 22’ 23” North latitude and 30° 44’ 32” to 30° 44’ 39” East longitude) (Fig.1) was chosen as the study area. The pond measured 165 meters in length, 65 meters in width, and approximately 1.5 meters in depth.

Study design

This six-month study was divided into three two-month periods, representing the three escalating fish activities (assuming the logical build-up of fish activity due to its growth, which was ensured visually during every sampling trip) between November 2021 and April 2022 to assess the impact of the increasing tilapia size and activity on MC. The tilapia stocking density was 20000 fish/acre (5 fish/m^3). The initial average fish weight at the first FA period was 16.96±0.25 g and 91.11±5.62 g, and 199.8±0.34 g in the subsequent (FA) periods, respectively. At the commencement of each period, nine replicates of each (AS) (pan scorers as inorganic substrate and *Luffa aegyptiaca* pieces, customised to match the dimensions of the pan scorers as organic substrate) were labelled and placed interspersed at the sediment-water interface of the pond bed along its sloping edges (Fig.1). Care was taken in spacing the (ASs) to minimize meiofaunal disturbance during collection after a two-week colonization period. Concurrently with (ASs) collection, nine sediment core samples were also collected to gauge the substratum effect. All substrates data were standardized by converting them to per cubic metre.

Biotic sampling

The two-week colonized substrates and the sediment samples were placed in plastic bags, preserved in 10% buffered formalin, and stained with 0.01% Rose Bengal for further laboratory examination.

Abiotic sampling

Nine more sediment core samples were collected and immediately placed in an icebox to be transported to the laboratory to analyze median sediment grain size and organic content. Water Quality was gauged in the field using Aquaprobe® AP-700 Multiparameter (temperature (°C), total dissolved solids (TDS) (mg/l), oxidation–reduction potential (ORP) (mv), conductivity (S/cm), dissolved oxygen (% and mg/l), and salinity (PSU)).

Sediment median grain size determination

The sediment median grain size was assessed according to the modified method of Buchanan [28], as suggested by Palmer and Strayer [29]. The sediment samples were washed through a series of stacked sieves (500, 250, 125, and 63 µm at the bottom) over a bucket to collect the smaller median grain sizes. The weight contribution of sediment by percentage in each sieve was then calculated. A known volume of the fine sediment suspension from the bucket was collected for the smaller size fraction (16 & 31 µm) calculations via a technique based on the graduated cylinder sedimentation rate, dried, and then weighed. Its percentage was estimated relative to the original sediment sample.

Organic matter determination (loss-on-ignition method)

A small amount of thawed sediment sample was placed in a preweighted porcelain crucible and dried in a 70 °C oven (overnight), according to Ben- Dor and Banin [30]. The sample was reweighed after cooling in a desiccator. The sediment sample was burned for six hours at 550 °C in a muffle furnace to ash the silt. After cooling, it was rewetted with deionized water, dried overnight in a 70 °C oven, placed in a desiccator, and weighed again. The percentage of mass loss is equal to the amount of organic matter in the sediment sample.

Meiofauna extraction

Meiofauna were extracted using the density gradient technique described by Somerfield and Warwick [31]. Wet-sieving process (500 µm sieve over a 45 µm mesh sieve) was used to collect the meiofaunal fraction, by mixing with a 1.15 density LUDOX® TM-50 colloidal silica gel solution in a tall beaker, and allowed to settle for one hour. The supernatant, containing the extracted meiofauna, was collected. The used Ludox was reused for two additional extraction attempts to maximize meiofauna recovery. The collected fauna was then washed into a Petri dish to be examined under a dissecting microscope or preserved in 70% ethanol for later analysis.

Meiofaunal biomass determination

Biomass (dry weight) was calculated following the method described by Ramsay et al. [32] using a National DC3-42OT digital dissecting microscope with an integrated camera. Motic 3.0 software, installed on a PC, was used for image analysis. The mean biomass was determined for eight taxa: Rotifera, Nematoda, Oligochaeta, Cladocera, Hydracarina, Ostracoda, Collembola, and Diptera larvae.

Statistical analysis

The PRIMER 6 and PERMANOVA+ programs [33] were used to assess the variabilities in environmental parameters, meiofaunal abundance, and biomass. The effects of artificial substrates and fish activities on abundance and biomass variabilities were assessed using Bray-Curtis similarities of fourth-root transformed meiofaunal abundance and biomass data, alongside Euclidean distance matrices of log+1 transformed and normalised environmental variables to evaluate the resemblance matrices. Nonmetric multidimensional scaling (nMDS) was plotted via resemblance matrices. An analysis of variance using permutation (PERMANOVA) was conducted to examine the effects of fixed factors (AS and FA) on meiofaunal abundance and biomass. The analysis included both main and pairwise comparisons. Significance levels were calculated from 999 random permutations of residuals under a reduced model. The distLM program was used to investigate the relationships among meiofaunal abundance, biomass, and environmental variables [34].

Results

Environmental variables

On the second sampling date (the second FA), most measured parameters (temperature °C, oxidation–reduction potential (ORP), dissolved oxygen percentage (DO%) and concentration (DO mg/l), conductivity (EC), total dissolved solids (TDS), salinity, and organic matter) were consistently low. The median grain size and pH, however, remained relatively stable across all three (FA) periods (Table 1).

PERMANOVA of log (x+1)-transformed environmental variables revealed a significant difference in the variables across the three (FA) periods (*Pperm* = 0.001). However, no significant differences in environmental factors were detected within the same (FA) period (*Pperm* = 0.672) (Table 2 and Fig.2).

Meiofaunal abundance

PERMANOVA of fourth-root transformed meiofaunal abundance and pairwise tests revealed significant differences for each of the inorganic and organic substrates among the three (FA) periods (*Pperm* = 0.001), except of the natural sediment (*Pperm* = 0.23). Similarly, MC differed among the three substrate types at each (FA) period (*Pperm* = 0.001) (Tables 3, and Fig.3). Within each fish activity period, meiofaunal abundance was significantly lower in natural sediment than in the inorganic and organic substrates.

Rotifera was the most abundant meiofaunal group, followed by Nematoda and Oligochaeta. Statistical analysis (DistLM) revealed that environmental variables had a weak influence on meiofaunal distribution, accounting for 8.2% (dissolved oxygen) to 39.2% (ORP) of the variation. In contrast, salinity had a decreasing effect on meiofaunal abundance during the three (FA) periods (50%, 38.5%, and 6.6%, respectively).

Meiofaunal biomass

Similarly, PERMANOVA showed a pattern comparable to that of abundance, revealing significant differences in meiofaunal biomasses across all substrates during the three (FA) periods. Additionally, meiofaunal biomasses differed significantly within the same activity period. However, this pattern only diverged from the abundance pattern in natural sediments in three cases: between the first (FA) and third (FA) (*Pperm* = 0.009), between the second (FA) and third (FA) (*Pperm* = 0.049) and within the three (FA) periods (*Pperm* = 0.021) (Table 4, Fig. 4).

A DistLM analysis revealed that environmental influences have a negligible influence on the distribution of meiofaunal biomass. However, salinity and ORP influenced meiofaunal biomass variabilities by 10.1% and 38.4% respectively. The impact of salinity decreased from the first to the second (FA) periods by 44% and 33.1%, respectively. In the third (FA), the dissolved oxygen content affected the biomass distribution by almost 6%.

Across all (FA) periods, natural sediment substrate presented significantly lower abundance and biomass than inorganic and organic substrates. These differences ranged from 7 to 15 orders of magnitude for abundance and from 2 to 12 orders of magnitude for biomass. In contrast, the variation in biomass and abundance between inorganic and organic substrates was relatively small, ranging from 1.1 to 1.6 orders of magnitude for abundance and from 1.25 to 2.5 orders of magnitude for biomass.

For the first (FA) period, meiofaunal abundance and biomass exhibited similar trends. Compared with those in a natural substrate, their levels were 15 and 12 times greater in inorganic substrate, respectively, and 9 and 6 times greater in organic substrate, respectively. However, inorganic substrate had 1.6 and 2 times greater meiofaunal abundance and biomass, respectively, than organic substrate.

At the second (FA) period, meiofaunal abundance and biomass were significantly greater in both organic and inorganic substrates than in the natural substrate. The abundance was 12.7 times greater in organic substrate and 11.2 times greater in inorganic substrate, whereas the biomass was 5 times greater in organic substrate and 4 times greater in inorganic substrate. Additionally, both the abundance and biomass were slightly greater in organic substrate than in inorganic substrate, with the abundance being 1.1 times greater and the biomass being 1.25 times greater.

The final (FA) period showed different meiofaunal abundance and biomass patterns. Compared with those in natural substrate, the abundance and biomass were 7 and 5 times greater, respectively, in inorganic substrate and 7.7 and 2 times greater, respectively, in organic substrate. The abundance was 1.1 times greater in organic substrate than in inorganic substrate, but the biomass was 2.5 times greater in inorganic substrate than in organic substrate

Discussion

Variability in sampling timing is likely to account for the observed variability in environmental parameters. This could be explained by the fact that there was no discernible difference between samples collected on the same Fish activity period [27, 35, 36]. During the second (FA) period (February and March), low conductivity, salinity, and oxidation-reduction potential (ORP) were all correlated with low total dissolved solute (TDS) concentration. Low oxygen levels can also result from other unknown causes, even though high oxygen levels are generally associated with low temperatures.

Several factors likely contribute to the higher meiofaunal densities observed in both inorganic and organic substrates than in natural substrate. First, the mucus excretions (biofilms) produced by colonizing organisms exhibit remarkable meiofaunal proliferation [37]. These biofilms, comprising 40–80% of prokaryotic cells [38], create highly dynamic and diverse physicochemical structures, ecological roles, and species compositions [39]. This diverse habitat offers a range of opportunities for meiofaunal growth and expansion [37]. Moreover, Peachey and Bell [35] emphasized the significant role played by harpacticoid copepods' mucus or mucus tubes in facilitating the colonization of sedimentary meiofauna. These tubes offer protection against various environmental stressors, both biotic (e.g., predation) and abiotic (e.g., UV radiation, desiccation, and strong currents). Furthermore, like filamentous algae, they can trap bacteria, detritus, and microalgae, creating a beneficial environment [40]. Second, meiofauna utilize organic and inorganic substrates as refugia from fish predation. This is evidenced by the inverse relationship between meiofaunal colonization and the increasing size and activity of the fish, which reduces the ability of meiofauna to evade being eaten/disturbed [35, 41]. Moreover, meiofauna and rotifers can actively migrate from sediment to the water column, presumably to avoid predation or habitat disturbances [42-44], reducing their abundance in the sediment and increasing their chance of colonizing AS. Third, new micro-niches provide opportunities for colonization by bacteria, protozoa, and small metazoans [45].

The general decrease in meiofaunal abundance and biomass during the third (FA) period was likely due to increased fish activity and the physical disturbance caused by their growth. This forces meiofauna to seek refuge deeper within the substrate, otherwise increasing their vulnerability to predation by fish [27]. These findings agreed with those of Mieczan [45]. He reported that the sediment disturbance caused by river currents enables various microorganisms and larger organisms to colonize exposed artificial surfaces. Additionally, he suggested that some microbes may have used the bottle's surface as a refuge from predators. These findings support the impact of predation and/or disturbance on meiofaunal abundance and biomass in the current study.

The high meiofaunal abundance and biomass observed during the second (FA) period may be attributable to external factors. Increased cattle

movement and farm worker activity in the surrounding area during this period could have displaced fish from the pond's marginal zones (where the artificial substrates were located). This displacement may lead to promoted meiofaunal colonization in these areas [27].

The lack of significant differences in meiofaunal abundance and biomass between organic and inorganic substrates, except for the third (FA) period, is consistent with the findings of Mieczan [45]. This similarity is likely due to the same eutrophication level and the similar texture of the artificial substrate in every period. Furthermore, increasing fish predation pressure likely forces meiofauna to utilize both artificial substrates equally as refuges. In contrast, meiofauna in natural substrate are likely more susceptible to heightened predation and/or disturbances because fish progressively increase in size and activity levels. Similarly, Bellou et al. [46] suggested that the substratum type and its orientation throughout the water column are less important than water depth in the composition of the colonized biofouling communities. Moreover, copepod colonization and species composition are influenced mainly by hydrothermal fluid input and temperature rather than by (AS) [47]. However, the significant variations in MC across (FA) periods in both inorganic and organic artificial substrates, but not in natural sediments, could be interpreted as follows. Due to the increasing size and activity of the fish across the three tested periods, resulting in escalating fish disturbance and/or predation, artificial substrates provide differential refuge capacities that suit fish activity variability. On the other hand, meiofauna in natural sediments are continuously susceptible to fish predation and/or disturbances such as top-down control without shelter, resulting in a consistent pattern of low MC.

The high rotifer abundance on artificial substrates aligns with the findings of Napiórkowski et al. [48], who suggested that light disturbances from water movement promote rotifer and crustacean presence and growth. This effect is likely amplified in the present study by the high fish density, which is supported by artificial substrate offering protection from fish predation, increasing the likelihood of invertebrate proliferation [49].

The high colonization rates of rotifers and nematodes corroborated previous findings [50]. These authors attributed rotifer success to several key characteristics, including the presence of preferred food sources (small algae, protozoans, and bacteria) within biofilms on artificial substrate. The resilience of worm-shaped meiofauna (like nematodes) during sediment recolonization after floods has also been documented [51]. Furthermore, the dominant rotifer groups in this study (*Bdelloidea*) possess pedal adhesive glands that secrete sticky cement for temporary attachment [52], further contributing to their efficient recolonization capabilities.

The discrepancy between the findings of this study and those of Mieczan [45], particularly regarding the influence of environmental variables, could be attributed to the dominant role of fish predation and/or disturbance, which may have masked the effects of other environmental factors.

The steady correlation between biomass and abundance indicates that changes in abundance have a greater impact on total biomass than does the average biomass of individual taxa [4]. This observation is consistent with the lower biomass observed in natural substrate during the third (FA) period, which correlated with reduced meiofaunal abundance, likely due to disturbance or predation by large-sized fish [27]. However, the difference in total biomass between organic and inorganic substrates during the third (FA) period may be explained by differences in the colonizing community structures. Specifically, the greater abundance of oligochaetes (1.5 times greater) and chironomids (twice as high) in inorganic substrate likely contributed to the divergence of the two substrate populations.

The recorded pelagic fauna colonization in both organic and inorganic artificial substrates in the current study is consistent with the findings of Mieczan [45], who suggested that animals transitioning from a free-swimming lifestyle to a sedentary lifestyle may do so to reduce predation pressure in the water column.

The texture of the artificial substrate is a crucial factor in meiofaunal colonization. Compared with the substrates used in the present study, smooth-surfaced substrates, such as the glass and plastic plates used by Mieczan [45], were less effective for colonization, both in terms of quality and quantity. The greater degree of colonization observed here likely resulted from the presence of interstitial spaces within the substrate. These spaces likely provided shelter from fish predators and/or disturbance and enhanced reproductive potential, contributing to higher meiofaunal colonization rates.

Conclusion

Compared to the natural substrate, artificial substrates, both organic and inorganic, significantly influenced meiofaunal colonization across all fish activity periods. However, no significant differences were observed between organic and inorganic substrates. Rotifera, Nematoda, and Oligochaeta were the most responsive taxa to the artificial substrates. Compared with environmental conditions, fish predation and/or disturbance appeared to be the strongest drivers of meiofaunal colonization and dispersal. The increased meiofaunal colonization and proliferation shown on artificial substrates strongly suggest their use in the earthen aquaculture ponds to

improve the sustainability of fresh natural food. However, further research investigating the effects of artificial substrates and fish activity periods on benthic freshwater meiofaunal colonization and their subsequent impact on fish growth parameters could lead to valuable improvements in earthen pond aquaculture practices.

Data availability

All relevant data are available from the authors upon request .The authors will provide raw data supporting the conclusions of this work to any qualified researcher.

Competing interests

The authors declare that they have no conflicts of interest.

Authorship statement

All the authors contributed equally to this work (i.e., in terms of conception, acquisition, sample analysis, statistical analysis, data interpretation, manuscript drafting, and manuscript revision).

Author contributions

All the authors accepted responsibility for the manuscript's content, consented to its submission, reviewed all the results, and approved the final version.

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TABLE 1. The means and standard deviations of the environmental variables measured at the three (FA) periods."

Environmental variables	(FA) periods		
	December 2021 (FA1)	February 2022 (FA2)	April 2022 (FA3)
***Temperature* (^{o}C)**	21.3±0.4	14.8±0.7	23.4±1.03
ORP	20.5±1	15±2.4	156.1±10.4
PH	7.6±0.2	7.6±0.07	7.2±0.06
***DO*%**	81.1±4.9	4.4±1.09	353.5±13.8
***DO* m/g**	7.2±0.6	0.4±0.2	29.9±1.09
***EC* ms/ cm**	2791.6±584	2233.3±308.06	3355.4±30.9
***TDS* mg/ l**	1806.2±37.9	1674.3±320.6	2178.7±24.2
***Salinity* PSU**	1.4±0.06	1.2±0.08	1.7±0.08
***Organic matter* (g)**	4±0.2	3.6±0.5	4.03±0.4
***Grain size* Φ**	16.3±0.1	16.4±0.1	16.5±0.2

These variables include temperature (°C), oxidation–reduction potential (ORP), pH, dissolved oxygen (DO) as a percentage and concentration (mg/ l), conductivity (EC), total dissolved solids (TDS), salinity, organic matter (g), and median grain size (Φ)"

TABLE 2. PERMANOVA results for log (x+1)-transformed environmental variables among the three (FA) periods, within every (FA) period, and their interaction.

Source	df	SS	MS	Pseudo-F	Unique *P*(*perm*)	Perms
Among (FAs) (A)	2	571.88	285.94	106.64	0.001*	996
Within (FA) (B)	2	3.149	1.5747	0.587	0.672	998
(A) X (B)	4	23.81	5.9525	2.2198	0.044*	999
Residuals	71	190.38	2.6815			
Total	79	790				

*Statistically significant ($P < 0.05$).

TABLE 3. Main and pairwise PERMANOVA results for meiofaunal abundance in the same substrate type among the three Fish activity (FA) periods and in the three substrate types within every Fish activity (FA) period. I= inorganic, O= organic, N= natural substrate.

	Main test							Pairwise test			
	Source	**df**	**SS**	**MS**	**Pseudo-F**	***P* (*perm*)**	**Unique Perms**	**Groups**	**t**	***P* (perm)**	**Unique Perms**
I	(FAs)	2	5761.1	2880.6	21.988	0.001*	999	FA 1 vs FA 2	4.2632	0.001*	981
	Residuals	24	3144.1	131				FA 1 vs FA 3	4.7925	0.001*	981
	Total	26	8905.2					FA 2 vs FA 3	5.0057	0.001*	974
O	(FAs)	2	5021.9	2511	22.713	0.001*	998	FA 1 vs FA 2	4.8253	0.001*	975
	Residuals	23	2542.7	110.55				FA 1 vs FA 3	4.8607	0.001*	975
	Total	25	7564.6					FA 2 vs FA 3	4.607	0.001*	978
N	(FAs)	2	902.94	451.47	1.3102	0.23	998	FA 1 vs FA 2	0.9605	0.416	981
	Residuals	24	8269.8	344.57				FA 1 vs FA 3	1.0179	0.414	982
	Total	26	9172.7					FA 2 vs FA 3	1.4127	0.094	975
FA1	(ASs)	2	8653.1	4326.5	20	0.001*	999	In. vs O.	1.2382	0.174	971
	Residuals	23	4975.5	216.33				In. vs N.	5.3196	0.001*	986
	Total	25	13629					O. vs N.	4.6609	0.001*	972
FA2	(ASs)	2	7293.7	3646.8	17.581	0.001*	999	In. vs O.	0.80657	0.599	980
	Residuals	24	4978.3	207.43				In. vs N.	4.4872	0.001*	975
	Total	26	12272					O. vs N.	4.5162	0.001*	977
FA3	(ASs)	2	4085.9	2042.9	12.249	0.001*	997	In. vs O.	1.0343	0.397	977
	Residuals	24	4002.7	166.78				In. vs N.	4.2062	0.001*	980
	Total	26	8088.6					O. vs N.	3.868	0.001*	978

*Statistically significant ($P < 0.05$).

TABLE 4. Main and pairwise PERMANOVA results for meiofaunal biomass in the same substrate type among the three Fish activity (FA) periods and in the three substrate types within every Fish activity (FA) period. I= inorganic, O= organic, N= natural substrate.

	Main test							Pairwise test			
	Source	**df**	**SS**	**MS**	**Pseudo-F**	***P* (*perm*)**	**Unique Perms**	**Groups**	**t**	***P* (perm)**	**Unique Perms**
I	FAs	2	3133.6	1566.8	16.526	0.001*	999	FA 1 vs FA 2	3.8855	0.001*	982
	Residuals	24	2275.5	94.812				FA 1 vs FA 3	4.3605	0.001*	978
	Total	26	5409.1					FA 2 vs FA 3	3.818	0.001*	971
O	FAs	2	2816.9	1408.5	19.385	0.001*	998	FA 1 vs FA 2	5.1284	0.001*	978
	Residuals	23	1671.1	72.657				FA 1 vs FA 3	4.3732	0.001*	976
	Total	25	4488					FA 2 vs FA 3	3.837	0.001*	989
N	FAs	2	1591.4	795.72	2.192	0.021*	997	FA 1 vs FA 2	1.1926	0.215	979
	Residuals	24	8712.4	363.01				FA 1 vs FA 3	1.7601	0.009*	978
	Total	26	10304					FA 2 vs FA 3	1.5185	0.049*	980
F	FAs	2	3133.6	1566.8	16.526	0.001*	999	In. vs O.	1.3939	0.087	980
A	Residuals	24	2275.5	94.812				In. vs N.	4.4229	0.001*	980
1	Total	26	5409.1					O. vs N.	3.763	0.001*	965
F	FAs	2	2816.9	1408.5	19.385	0.001*	998	In. vs O.	1.3531	0.117	978
A	Residuals	23	1671.1	72.657				In. vs N.	3.0754	0.001*	981
2	Total	25	4488					O. vs N.	3.22	0.001*	984
F	FAs	2	1591.4	795.72	2.192	0.021*	997	In. vs O.	2.4938	0.001*	978
A	Residuals	24	8712.4	363.01				In. vs N.	4.1606	0.001*	981
3	Total	26	10304					O. vs N.	3.578	0.001*	976

*Statistically significant ($P < 0.05$).

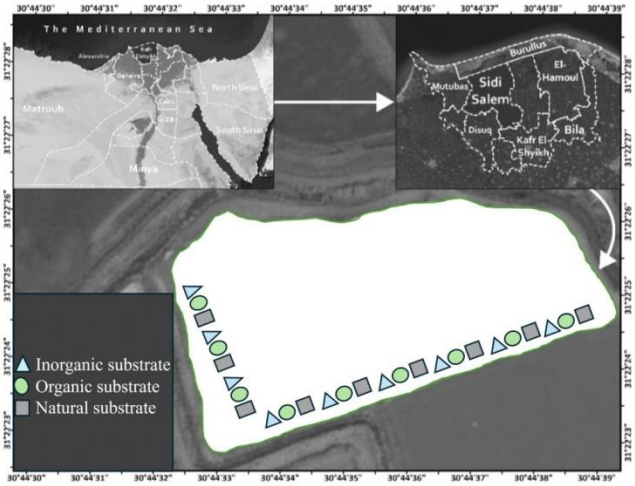

Fig.1. Study area map showing the experimental tilapia pond and the locations of natural and artificial substrate types (ASs) implemented during every fish activity (FA) period.

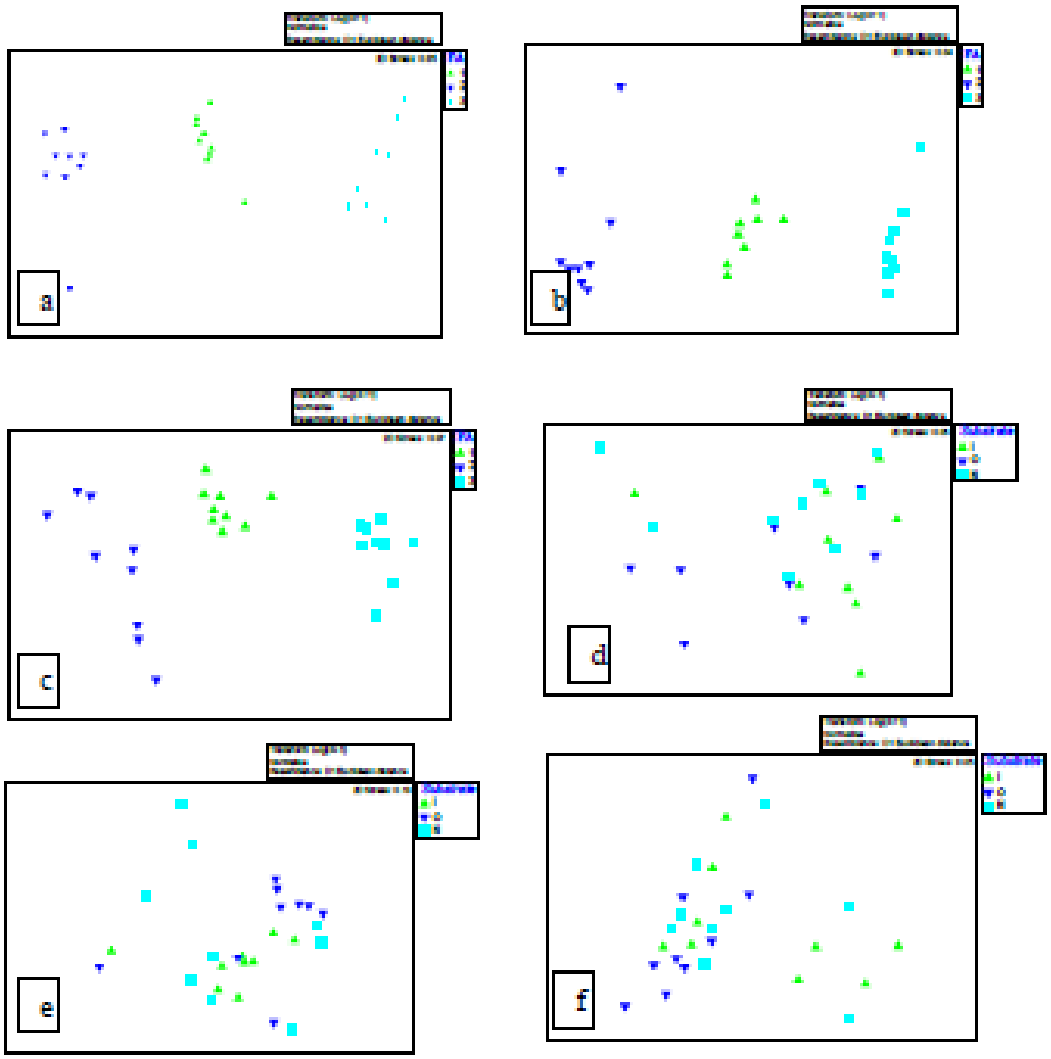

Fig. 2. Nonmetric multidimensional scaling (nMDS) ordination of environmental variables (log (x+1) transformed). The plot reveals two key findings: (1) Distinct environmental differences exist among the three (FA) periods (1, 2, and 3) at each substrate type (a, b, and c), and (2) no such differences are observed within the (FA) periods (d, e, and f). I, O, and N denote inorganic, organic, and natural substrates, respectively

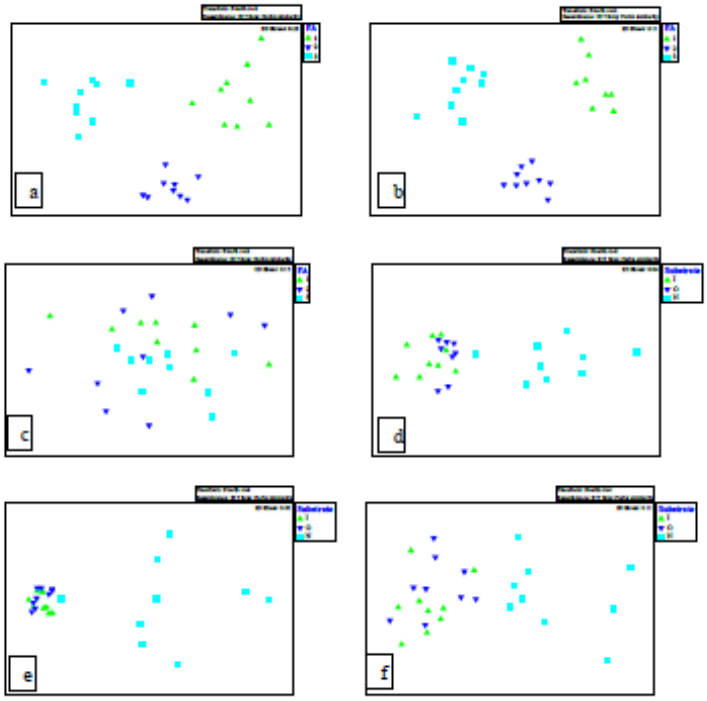

Fig. 3. Meiofaunal abundance in the three (FA) periods across the different substrates: (a) inorganic, (b) organic, and (c) natural. (d, e, f) represent the first, second, and third (FA) period, respectively. I = inorganic, O = organic, and N = natural substrate.

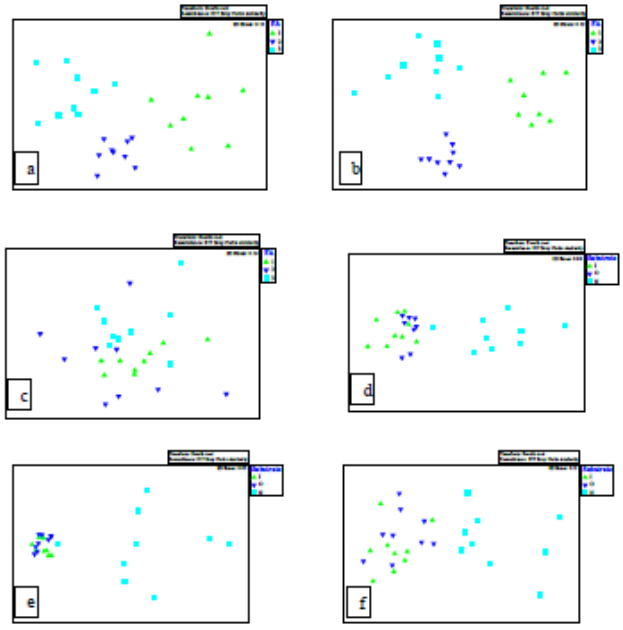

Fig. 4. Meiofaunal biomasses among the three subsequent (FA) periods for (a) inorganic, (b) organic, (c) natural substrate, (d, e, and f) first, second, and third (FA) period. I = inorganic, O = organic, and N = natural substrate.

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تأثير نوع الركيزة ونشاط الأسماك على استعمار الميوفونا في المياه العذبة

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الملخص

السياق :تمثل الميوفاونا (MC) مورداً غذائياً طبيعياً مهماً للكائنات المائية الأعلى، غير أنّ استجابتها الاستعمارية (من حيث الوفرة والكتلة الحيوية) لنوع الركيزة وللاضطراب البيئي ما زالت غير مفهومة بشكل كافٍ. **الأهداف :**هدفت هذه الدراسة إلى تقييم تأثير كلٍّ من نوع الركيزة (ركائز اصطناعية عضوية وغير عضوية (AS) مقابل الرواسب الطبيعية كعنصر ضابط) ونشاط الأسماك المتزايد (FA) بوصفه مصدراً للاضطراب، على استعمار الميوفاونا (MC) . **الطرق :**نُفِّذت الدراسة على ثلاث فترات متعاقبة (شهران لكل فترة) وفق تصور تصاعدي لنشاط الأسماك (FA) ما بين الفترة من شهر نوفمبر2021 الي شهر ابريل 2022 .في بداية كل فترة وُضعت تسع مكررات من الركائز العضوية وغير العضوية (AS) وأُعيد جمعها بعد أسبوعين من الاستعمار، إضافةً إلى تسع مكررات من الرواسب الطبيعية. كما جرى قياس المتغيرات البيئية المصاحبة.**النتائج :**لم تُظهر الركائز الاصطناعية (AS) فروقاً معنوية في مستويات استعمار (MC) فيما بينها، غير أنها اختلفت بشكل ملحوظ عن الرواسب الطبيعية في جميع الفترات. كما تباين استعمار (MC)بوضوح بين الفترات الثلاث من(FA) ، باستثناء حالة الرواسب الطبيعية. وقد سُجّل أدنى مستوى من الاستعمار خلال الفترة الثالثة من (FA) على جميع أنواع الركائز.**الاستنتاج :**أظهرت النتائج أنّ الركائز الاصطناعية (AS) وفّرت حماية لاستعمار الميوفاونا (MC) من الافتراس أو الاضطراب الناجم عن نشاط الأسماك(FA) ، مما عزز تكاثرها وإفرازها للمخاط، وأسفر عن تكوين بيئات دقيقة متباينة تدعم الاستعمار.**التبعات :**يُحتمل أن يسهم تعزيز تكاثر الميوفاونا (MC) في دعم استدامة تغذية الأسماك ضمن أنظمة الاستزراع المائي، إلا أنّ مزيداً من البحوث يبقى ضرورياً لتحسين هذه الاستراتيجية.

الكلمات المفتاحية: الوفرة، النشاط، الكتلة الحيوية، استعمار الميوفاونا، الركيزة.