Semi-empirical and Semi-quantitative Lightweight Shielding Design Algorithm

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Abstract

Lightweight shielding design for small reactors is a topic of significant research interest. Based on a small helium-xenon-cooled solid reactor, the effects of shielding layer thickness and layer count on radiation dose are first investigated. It is found that when photons are shielded first and the number of shielding layers is odd, the radiation dose can be significantly reduced. To reduce the weight of the shielding assembly, the relative thicknesses of the shielding layers are optimized using a genetic algorithm. The optimized design can reduce the radiation dose by up to 57% while achieving an 11.84% weight reduction. To determine the total thickness of shielding layers and avoid local optima, a formula establishing the relationship between total thickness and radiation dose is derived through large-scale calculations, which exhibits an error of 0.8%–7.45% compared to the Monte Carlo method. A semi-empirical and semi-quantitative lightweight shielding design algorithm is proposed to integrate the aforementioned work, and the SDIC1.0 code is developed to achieve optimized lightweight shielding design for small reactors. Verification shows that the error between SDIC1.0 and the Monte Carlo code RMC is approximately 10%, and the computational efficiency has increased by a factor of 6.3.

Full Text

Preamble

Semi-empirical and semi-quantitative lightweight shielding design algorithm

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ABSTRACT

The lightweight shielding design of small reactors represents a prominent research focus. Based on a small helium-xenon-cooled solid reactor, we first investigated the effects of neutron and photon shielding sequence and the number of shielding layers on radiation dose. Our findings revealed that shielding photons first with an odd number of layers significantly reduces radiation dose. To further reduce shielding weight, we optimized the relative thickness of shielding layers using a genetic algorithm (GA). The optimized scheme achieved up to 57% reduction in radiation dose and 11.84% weight reduction. To determine the total shielding thickness and avoid local optimal solutions from the GA, we developed a series of formulas describing the relationship between total thickness and radiation dose through large-scale calculations. We propose a semi-empirical and semi-quantitative lightweight shielding design algorithm that integrates the above optimization methods and verify it using the Monte Carlo method. Finally, we developed the SDIC1.0 code to achieve optimized lightweight shielding design for small reactors. Verification shows that the difference between SDIC1.0 and the RMC code is approximately 10%, while computation time is reduced by 6.3 times.

Keywords: Small reactor; Lightweight; Shielding calculation; Genetic algorithm

1. INTRODUCTION

Owing to their specific applications, small reactors face stringent requirements for mobility and safety, which strictly limit reactor size and weight. Consequently, lightweight shielding design is vital for small reactors and primarily depends on material selection and shielding layer arrangement to achieve a lightweight, compact, and effective shielding configuration.

Lightweight shielding design requires balancing multiple parameters including mass, volume, and radiation dose [1-3]. The Monte Carlo method effectively addresses complex shielding problems involving intricate structures, non-uniformity, and strong anisotropy, and numerous reactor shielding designs based on this method have been reported [4-7]. However, applying the Monte Carlo method to shielding design based on traditional experience is inefficient

and costly, making it challenging to meet the demands of small reactor shielding design. Furthermore, when shielding layer thickness exceeds a certain range, deep penetration problems [8-9] cause Monte Carlo results to deviate significantly from theoretical values [10], leading to convergence difficulties [11-12].

Various optimization algorithms have been proposed to improve lightweight shielding design efficiency. With the rapid development of optimization techniques, scholars have applied related algorithms to shielding design [13-15]. Intelligent optimization algorithms such as genetic algorithms (GA) [16-17], particle swarm optimization (PSO) [18], and neural network algorithms [19] are typically heuristic. With appropriate parameter settings, these algorithms can reduce optimization time and have been widely used in shielding material development [20] and shielding component optimization [21]. Reactor shielding optimization methods based on these algorithms can improve computational efficiency.

Nevertheless, general heuristic algorithms can easily produce local optimal solutions when parameter settings are unreasonable. In such cases, it cannot be verified whether the generated optimal solutions are truly global [22], potentially wasting resources during actual design. Two fundamental approaches exist to avoid local optimal solutions [23]. The first involves in-depth study of the problem mechanism by establishing mathematical equations to determine extreme values or identify the intervals where they occur. The second employs random search methods. For discrete problems, increasing search randomness can reduce the probability of local optima. Standard random search methods such as roulette, Gaussian mutation, Cauchy mutation, and Gauss-Cauchy hybrid mutations have been widely applied [24]. However, regardless of the method employed, local optimal solutions cannot be completely avoided when models become excessively complex or information processing demands are too large.

In this study, we established an empirical shielding design method to determine the number of shielding layers and neutron/photon shielding order through systematic numerical simulations. Subsequently, we applied GA to optimize the relative thickness of shielding layers. Finally, we established the relationship between total shielding layer thickness and dose through extensive calculations across different power ranges, proposing a quantitative shielding design method. This method provides a quantitative solution for total shielding thickness based on power and core design parameters before GA optimization of individual layer thicknesses. By incorporating this quantitative solution and dose limits as constraints, GA optimization can avoid local optimal solutions. We used the Reactor Monte Carlo (RMC) software to verify the accuracy of our method in terms of shielding effectiveness and weight reduction.

The results demonstrate that our semi-empirical and semi-quantitative lightweight shielding design method can rapidly determine an optimal shielding scheme to achieve weight reduction goals. The remainder of this paper is organized as shown in Figure 1 [Figure 1: see original paper].

2.1 Core Design and Source Characteristics

Our shielding design is based on a small helium-xenon-cooled reactor, as illustrated in Figure 2 [Figure 2: see original paper]. The core features a repetitive hexagonal internal structure comprising 1040 fuel rods with a diameter of 1.5 cm, surrounded by six coolant channels with a diameter of 0.8 cm. The core has an overall radius of 44 cm, total height of 100 cm, and design power of 20 MW.

The core uses graphite as the base material, with fuel rods filled with uranium carbide (UC) composed of 19.75% enriched uranium, and coolant cladding made of Titanium-Zirconium-Molybdenum (TZM) alloy. The core is surrounded by a 20 cm thick Be reflector. B_4C is a functional ceramic material with excellent properties, particularly high thermal neutron absorption capacity, and was selected as the neutron shielding material. Stainless steel, containing iron and widely used for photon shielding, was selected as SS-316 stainless steel for photon shielding.

We defined the reactor source term as a volume source. For a reactor operating at full power, each fission releases 180.912 MeV of energy (1 MeV = 1.602$×10^{-13}$ J). The number of neutrons produced per fission is assumed to be 2.45. If k ff = 1, then every 2.45 source neutrons provided by the core will induce one fission (with remaining neutrons being absorbed or escaping). This represents the number of fission neutrons required per unit time for each 1 J of energy released by the system. For power P, the source intensity A is calculated accordingly.

2.2 Basic Shielding Schemes with Empirical Method

As shown in Figure 3(a) [Figure 3: see original paper], we set the total shielding thickness to 100 cm with uniform layer thickness and varied the number of layers (limited to 3-16) to explore the variation pattern of radiation dose rate.

We further classified schemes according to the shielding sequence for neutrons and photons. Statistical results for large particle populations were equivalent to large-scale repeated simulations of single particles under identical conditions. However, with continuously increasing particle numbers, it cannot be guaranteed that all particles will be captured or absorbed by shielding material, as some will penetrate the shielding layer to reach the outer vacuum boundary. By establishing detection areas and counting radiation dose within them, shielding layer designs can be evaluated. Since dose is not uniformly distributed along the axis, we added a 5 cm thick air annulus at the shielding periphery as the detection area, divided uniformly into 20 axial zones with a total height of 20 × 5 cm = 100 cm. As shown in Figure 3(b), we calculated dose in each zone

to determine the radial dose distribution (mrem/h) across 20 axial zones for six trial plans.

Statistical analysis shows that maximum dose values appear in the middle zones, while minimum values occur at both ends, as illustrated in Figure 3(c). Shielding calculations were performed using the Monte Carlo software RMC, and the variation of maximum/minimum radiation dose in the detection area with layer number and particle shielding order is shown in Figure 3(d).

As shown in Figure 3(d), with constant total thickness, when neutrons were shielded first (NSF), the dose rate was negatively correlated with the number of shielding layers and eventually converged to a certain range. Moreover, the radiation dose rate was lower when the total number of layers was even. When photons were shielded first (PSF), the dose rate did not decrease or converge significantly with increasing layer number, but was relatively low when the number of layers was odd. Compared to the NSF scheme with the same number of layers, the dose was reduced by 3-5 times. The dose difference between odd and even layer numbers must be explained in conjunction with particle transport processes in the reactor. Neutron scattering in the reactor generates photons; if neutrons can be effectively shielded, this is equivalent to pre-shielding a portion of photons. For example, with NSF and four layers, B_4C in the first and third layers shields most neutrons, resulting in fewer secondary photons that can be absorbed by SS-316 in the outermost layer, yielding a dose significantly lower than a three-layer design with the same total thickness.

Therefore, we propose two empirical shielding schemes: (1) Scheme I: shield photons first with an odd number of layers, and (2) Scheme II: shield neutrons first with an even number of layers.

3.1 Relative Thickness Optimization with GA

The empirical method determines the number of shielding layers and neutron/photon shielding order. These parameters were not considered in subsequent optimization and could be directly used as modeling bases for the shielding body. However, the empirical method cannot optimize relative layer thickness as it only provides uniform thickness schemes. To further reduce weight, we employed GA to optimize relative shielding layer thickness.

Figure 4 [Figure 4: see original paper] shows the GA flowchart. Genetic manipulation of radiation shielding schemes primarily includes population selection, crossover, and mutation, discussed separately below.

1) Selection: Suppose the population size is m and the fitness of individual i is F ; then, the probability P of individual i being selected is calculated accordingly.

2) Crossover: We used the single-point crossover operator, randomly selecting a position in paired chromosomes and performing locus transformation at the

selected position.

3) Mutation: To ensure individual diversity, continuous mutation during iteration is necessary. This study adopted the single-point mutation method, where only a specific bit in the gene sequence needs to be mutated using binary coding as an example.

The mathematical function model for solving optimal thickness of each layer under different layer-arrangement schemes is formulated as follows: $y = F(x)$, where x is the n-dimensional design variable, $x = (x_1, x_2, \ldots, x)$ X, including shielding material selection, number of layers, and initial thickness of each layer. X represents the design variable value space. A hybrid coding method was adopted: binary coding expressed the order of each shielding layer in each scheme, while symbol coding expressed the material type assigned to a single layer. Here, we selected only B_4C and SS-316 stainless steel as shielding material inputs. y is the m-dimensional design objective, which in this study includes the lowest achievable levels of maximum and minimum radiation doses in each detection area, as well as the total weight of the shielding body.

Simultaneously, the fitness function during GA operation was determined according to these design goals. $f_3(x)$–$f_{16}(x)$ represent different schemes with 3-16 shielding layers, respectively. $g(x) \leq 0$ defines q inequality constraints, and $h(x) = r$ defines p equality constraints. When iteration stop conditions are satisfied, the optimal solution can be output according to fitness ranking.

The shielding design problem is essentially a multi-objective optimization problem where conflicts between sub-objectives are inevitable. To better reflect the importance of certain sub-objectives, it is necessary to reasonably set the weight of each sub-objective in the fitness function. This study adopts the Analytic Hierarchy Process (AHP) to determine each index weight and select the optimal solution [25].

AHP is an efficient method for defining weights of sub-objectives in multi-objective optimization problems, offering advantages of minimal information requirements and short decision-making time. The AHP steps are as follows:

1) Create a positive reciprocal matrix where each element's value is determined using Table 1 . For example, when comparing the total shielding body weight to the lowest achievable maximum dose in the detection area, if the former is significantly more important than the latter, then $a_{12} = 5$ and $a_{21} = 1/5$. Each indicator was compared with others to determine the reciprocal matrix A.

2) Perform consistency check: Normalize each column vector of matrix A, sum rows to obtain normalized weights, then calculate the eigenvector $w = (w_1, w_2, \ldots, w)$. The consistency factor is given by $CI = (\lambda - m)/(m - 1)$, where m is the order of matrix A. CI is compared with the random consistency factor RI from Table 1 to calculate the consistency ratio $CR = CI/RI$. When $CR < 0.1$, matrix A meets consistency standards; otherwise, it must be modified. After passing the consistency test, eigenvector w provides the required weight vector.

To improve the probability of obtaining optimal solutions, the population size was set to 50 with 100 evolutionary generations. Previous research indicates that mutation probability exceeding 0.04 yields unstable results, so we set mutation probability to 0.02. Simultaneously, to achieve better local search capability, crossover probability was set to 0.5 [26]. Schemes with 7-13 shielding layers were selected as calculation samples, and statistical doses under different shielding layer configurations are summarized in Table 2 and Figure 5.

As shown in Table 2 and Figures 5(a) and 5(b), when neutrons are shielded first, the dose rate from GA-optimized schemes is significantly lower than the initial series schemes shown in Figure 3(a), with maximum reduction reaching 57%. When photons are shielded first, the difference between optimized and initial scheme dose rates gradually decreases as layer number increases.

The relative thickness distributions of optimized schemes are summarized in Table 2. Combined with pre- and post-optimization thickness distributions, the results in Figure 5 can be divided into two types: Type 1 involves neutron-first shielding with odd total layers, or photon-first shielding with even total layers; Type 2 involves neutron-first shielding with even total layers, or photon-first shielding with odd total layers—the two schemes presented at the end of Chapter 2. Considering Table 2 results and particle transport processes, most particles are absorbed because the shielding layer near the core is thicker. In Type 1 cases, because the outermost layer is B_4C which absorbs some remaining neutrons, the relative change rate before and after optimization is more evident, as shown in Table 2. However, the overall dose level of Type 1 is higher than Type 2, so we excluded Type 1 cases. Additionally, when layer number increases in Figure 5(b), the pre- and post-optimization dose remains unchanged, implying that relative thickness of each layer decreases and corresponding particle absorption capacity worsens, similar to schemes with uniform layer thickness.

The weight of each shielding scheme was then calculated, with results shown in Figure 5(c). Referring to Figure 3(d), following Scheme I reduces weight to a certain extent, while following Scheme II increases weight despite dose reduction. Therefore, we recommend Scheme I. Moreover, relative thickness optimization with GA helps reduce shielding layer weight.

3.2 Determination of Total Thickness with Quantitative Correlation

Research shows that when applying GA to reactor shielding design, genetic operators (population size, crossover probability, mutation probability) are typically determined by presetting different initial values [26]. Appropriate operator values are then determined by counting the average number of individuals required to achieve optimal solutions under different combinations, which are finally input into the algorithm framework. This process involves extensive calculation and strong repeatability, seriously affecting overall shielding design efficiency.

To avoid repeating this process, this section proposes a method for directly and quantitatively constraining the algorithm by providing total shielding layer thickness through dose relationships.

In this study, the GA-optimized scheme provides relative thickness of each shielding layer determined according to design target y. Since total shielding body weight and dose settings in y are estimated values (upper limits of corresponding value ranges), any solution within the range satisfying these values may be considered optimal. Additionally, the algorithm exhibits forward iteration characteristics, making it generally impossible to determine whether the total weight obtained by summing relative thicknesses represents the global optimal solution in shielding design. Therefore, total thickness can be determined through shielding calculations as a quantitative constraint for the GA optimization process to avoid local optimal solutions [27].

Total thickness is related to radiation dose requirements. Generally, the best approach is to perform accurate Monte Carlo shielding calculations to determine total thickness based on dose requirements. However, when an approximate value range cannot be obtained, the process of obtaining ideal results using Monte Carlo methods is usually random. To improve design efficiency, we established a quantitative relationship between total thickness and dose requirements through mass calculations in advance, enabling direct determination of total shielding layer thickness according to dose requirements to establish complete shielding schemes.

As shown in Figure 6(a) [Figure 6: see original paper], thickness and dose exhibit an exponential relationship. The thickness-dose design curves in logarithmic coordinate systems are shown in Figure 6(b).

We first established a set of equations between dose rate and total thickness at constant power (20 MW). The maximum equation is calculated as follows, and the minimum equation is calculated accordingly. In these equations, T is the total thickness of the shielding layer (cm) and D = lg(a), where a = dose (mrem/h).

To verify calculation accuracy of these equations, three thickness sets (T_1–T_3) were randomly selected, and maximum and minimum dose results (D_1Max–D_3Max; D_1Min–D_3Min) were calculated using the equations. T_1–T_3 were substituted as quantitative constraints into the GA toolbox ($h_1(x) = T_1$, $h_2(x) = T_2$, $h_3(x) = T_3$). Total shield weight and dose ranges were set simultaneously. Design variables were entered into the x-dimensional vector space, and the fitness function was set according to the AHP method. The obtained results (relative thickness of each layer) together with other design variables were used as RMC input parameters. The comparison between RMC-calculated doses and equation-calculated doses is shown in Figure 6(c).

As shown in Figure 6(c), compared with RMC results, the relative error of extreme dose values in all detection areas calculated by the equations is within 10%. The validity and accuracy of the quantitative solution provided by these

equations were verified and can be applied to rapid shielding design calculations for small reactors.

Generally, reactors with power levels of 5-200 MW are considered small reactors. Based on the above results, to improve equation universality, we extended the power range to 5-200 MW and specified the thickness-dose relationship for different power levels, as illustrated in Figure 7 [Figure 7: see original paper]. Under actual design conditions, designers typically focus on maximum dose in detection areas; therefore, the relationship between thickness and maximum dose is provided.

Combined with conclusions from Chapter 2 and Section 3.1, assuming particle shielding order is determined, Table 2 shows that when the number of shielding layers is set to 7, the GA-optimized shielding scheme yields the smallest dose value compared to other schemes. Therefore, the number of shielding layers was set to 7, with results shown in Figure 8 [Figure 8: see original paper].

As observed, the thickness-dose relationship at different power levels continues to follow exponential change. The quantitative relationship can be summarized as follows: $D = a \times e^{\wedge}(bT)$, where a represents the dose accumulation factor and b represents the dose correction factor.

When reactor design power is given, specific values of accumulation factor a and correction factor b are first determined through their relationship. These factors are then substituted into the equation, and the corresponding total shielding layer thickness is quantitatively determined according to dose limits. Combined with the empirical design method and multi-objective optimization method proposed above, the final optimized design scheme can be obtained.

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4. EFFECT EVALUATION OF THE METHOD

This section verifies the weight-loss effect of the proposed semi-empirical and semi-quantitative shielding design method and develops it into a shielding design program.

4.1 Evaluation of Shielding and Weight-Loss Effect

To simultaneously verify the effect of our semi-empirical and semi-quantitative shielding design method on radiation shielding and weight reduction, we established three sample groups for comparison. First, the power of the three sample groups was randomly set to P = 37.5 MW, with dose D_1 = 100 mrem/h. The total shielding layer thickness was obtained from the equation as T_1 = 119.7 cm. Based on the empirical shielding design method, the shielding body model was established according to Scheme I. Material, number of shielding layers, and initial thickness of each layer were entered as design variables into the GA model. With D_1 and T_1 as quantitative constraints in the GA optimization process ($h_1(x) = 100$, $h_2(x) = 119.7$), the optimized relative thickness from inner

to outer radius is shown in Figure 9(a) [Figure 9: see original paper] and Table 3 .

Compared with a shielding scheme having equal total thickness (T_2 = T_1 = 119.7 cm) and equal relative thickness of each layer (t_2 = 17.1 cm), neutron/photon coupling transport calculations were performed. The total shielding layer weight and dose in each detection area for the two schemes are listed in Table 3 and Figure 9(b). Under the same total thickness condition, the semi-empirical and semi-quantitative shielding design method effectively reduces radiation dose by approximately 2.3 times, decreasing the maximum detection area dose from D_2 = 235.23 mrem/h to D_1 = 101.04 mrem/h. Similarly, when dose requirements are equal (D_3 = D_1 = 100 mrem/h), the method reduces total shielding body weight from 60.71 t to 53.52 t, representing an 11.84% reduction compared to the conventional method (same dose requirement).

Additionally, we provide a two-layer design scheme. To ensure the same particle shielding order, SS-316 and B_4C were each set as single layers, with thicknesses referenced from the scheme in the second column of Table 3, such that the sum of the two layer thicknesses is 119.7 cm. The maximum dose calculated by this scheme is 4527.29 mrem/h, which is 42 times higher than the scheme optimized by our semi-empirical and semi-quantitative lightweight shielding design method.

In summary, treating power as an independent design variable and deriving accumulation factor a and correction factor b, then substituting these factors into the thickness equation, can constrain total thickness before GA optimization of individual layer thicknesses. This effectively avoids local optimal solutions due to large calculation scales.

4.2 Shield Design Optimization Program SDIC1.0

We encapsulated the semi-empirical and semi-quantitative lightweight shielding design method into SDIC1.0. The method comprises three steps: (1) Determine the number of shielding layers and neutron/photon shielding sequence through trial calculations to establish an empirical scheme; (2) Establish the thickness-dose relationship through statistical analysis of extensive Monte Carlo calculation results to determine corresponding total shielding layer thickness from dose requirements, using this thickness as a constraint to prevent local optimal solutions during relative thickness optimization; (3) Optimize relative shielding layer thickness using GA to reduce shielding weight. To encapsulate this method, we developed the shield optimization design program SDIC1.0, with the process illustrated in Figure 10 [Figure 10: see original paper].

The program's accuracy was verified by randomly setting different power levels and dose limits based on a consistent core scheme. As shown in Table 4 , three random power groups were 60 MW, 140 MW, and 110 MW, respectively. First, accumulation factor a and correction factor b were obtained from input power. Three dose limits at different power levels were then set: D_1 = 10000 mrem/h,

D_2 = 5000 mrem/h, D_3 = 1000 mrem/h. Corresponding total shielding layer thicknesses were determined from dose limits. The process from Section 4.1 was repeated: design variables and constraints were entered, the algorithm was run, and outputs including relative thickness of each layer were obtained. Finally, GA-optimized layer thicknesses were used as RMC inputs, and calculated doses were compared with initially set doses D_1–D_3, with results presented in Table 4.

As shown in Table 4, the relative error between SDIC1.0 and RMC results can be effectively controlled at 9.63%, 10.40%, and 11.40%, respectively. Error analysis suggests that fewer sample points were used when determining the relationship between power and factors a and b, resulting in some deviation in fitting. In the future, error from program calculations can be reduced by increasing initial sample point density.

Regarding computation time, as shown in Table 4, T_1 represents the time required to obtain the optimal solution using our proposed method, while T_2 represents the time required to obtain similar results using only the Monte Carlo code RMC. Our method reduces calculation time by approximately 6.3 times.

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5. CONCLUSION

This study investigated shielding design methods for a small helium-xenon reactor. First, we proposed an empirical shielding design method based on core parameters. Guided by design objectives and combined with empirical methods, we applied GA to optimize relative layer thickness and evaluated the weight-loss effect compared with conventional schemes. To address potential local optimal solutions from GA, we proposed a quantitative design method based on large-scale Monte Carlo calculations that determines total shielding layer thickness according to power and dose requirements before GA optimization. This total thickness serves as a quantitative constraint during algorithm execution. Finally, we integrated these processes into a semi-empirical and semi-quantitative lightweight shielding design method. This method offers advantages in shielding effectiveness, weight reduction, computational efficiency, and accuracy. Specific conclusions from each chapter are summarized as follows:

1. An empirical shielding scheme is proposed: photons are preferentially shielded with an odd number of shield layers.
2. The thickness-dose relationship under different power levels is established. Verification shows that when combined with empirical methods, the GA-optimized shielding scheme reduces weight by 11.84% compared to conventional schemes.
3. The method was encapsulated into the shielding design program SDIC1.0. Test results show that under the same shielding scheme, the difference

between SDIC1.0 and Monte Carlo software RMC is controlled at approximately 10%, while computation time is reduced by 6.3 times.

The semi-empirical and semi-quantitative lightweight shielding design method can rapidly determine shielding schemes and provide initial solutions for more detailed shielding optimization. Future work will propose more universal methods by introducing energy spectrum characteristics and material physical properties. Additionally, this study focused primarily on refined design of radial shielding layers. Since axial dose field distribution differs significantly from radial distribution, further research on axial dose-field distribution is necessary for axial shielding layer design.

Author Contributions

All authors contributed to study conception and design. Material preparation, data collection, and analysis were performed by Song-Chuan Zheng and Qing-Quan Pan. Resources and supervision were provided by Huan-Wen Lv, Song-Qian Tang, and Xiao-Jing Liu. The first draft was written by Song-Chuan Zheng, and all authors commented on previous versions. All authors read and approved the final manuscript.

Data Availability Statement

The data supporting this study's findings are openly available in the Science Data Bank at https://www.doi.org/[data DOI number] and http://resolve.pid21.cn/[data CSTR number].

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Note: Figure translations are in progress. See original paper for figures.