Traveling wavefronts for time-delayed reaction–diffusion equation: (II) Nonlocal nonlinearity

Ming Mei\textsuperscript{a,b,*}, Chi-Kun Lin\textsuperscript{c}, Chi-Tien Lin\textsuperscript{d}, Joseph W.-H. So\textsuperscript{e}

\textsuperscript{a} Department of Mathematics, Champlain College Saint-Lambert, Saint-Lambert, QC, J4P 3P2, Canada
\textsuperscript{b} Department of Mathematics and Statistics, McGill University, Montreal, QC, H3G 1M8, Canada
\textsuperscript{c} Department of Applied Mathematics, National Chiao Tung University, Hsinchu 30010, Taiwan, ROC
\textsuperscript{d} Department of Applied Mathematics, Providence University, Taichung 43301, Taiwan, ROC
\textsuperscript{e} Department of Mathematical and Statistical Sciences, University of Alberta, Edmonton, AB, T6G 2G1, Canada

\section*{Abstract}
This is the second part of a series of study on the stability of traveling wavefronts of reaction–diffusion equations with time delays. In this paper we will consider a nonlocal time-delayed reaction–diffusion equation. When the initial perturbation around the traveling wave decays exponentially as $x \to -\infty$ (but the initial perturbation can be arbitrarily large in other locations), we prove the asymptotic stability of all traveling waves for the reaction–diffusion equation, including even the slower waves whose speed are close to the critical speed. This essentially improves the previous stability results by Mei and So \cite{MeiSo08} for the speed $c > 2\sqrt{D_m(3\varepsilon p - 2d_m)}$ with a small initial perturbation. The approach we use here is the weighted energy method, but the weight function is more tricky to construct due to the property of the critical wavefront, and the difficulty arising from the nonlocal nonlinearity is also overcome. Finally, by using the Crank–Nicholson scheme, we present some numerical results which confirm our theoretical study.

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1. Introduction

Subsequently to [16], as the second part of this series of study, we further investigate the nonlocal time-delayed reaction–diffusion equation

\[
\frac{\partial v}{\partial t} - D_m \frac{\partial^2 v}{\partial x^2} + d_m v = \varepsilon \int_{-\infty}^{\infty} b(v(t - r, x - y)) f_\alpha(y) \, dy, \quad (t, x) \in (0, \infty) \times \mathbb{R},
\]

(1.1)

with the initial condition

\[ v(s, x) = v_0(s, x), \quad (s, x) \in [-r, 0] \times \mathbb{R}. \]

(1.2)

The model (1.1) describes a single-species population with age-structure and diffusion (cf. [24]). Here, as explained in [16], \( v(t, x) \) denotes the total mature population of the species (after the maturation age \( r > 0 \)) at time \( t \) and position \( x \). \( D_m > 0 \) is the diffusion rate of the mature species, \( d_m > 0 \) is the death rate of the matured, \( \alpha > 0 \) is the total amount of diffusion for the immature species, and it is assumed to satisfy

\[ \alpha \leq r D_m, \]

(1.3)

namely, the immatured is less mobile than the matured, and \( \varepsilon > 0 \) represents the impact of the death rate of the immature. The birth function \( b(v) \) is one of the following two important types (see [12, 16])

\[ b_1(v) = p v e^{-av^q}, \quad \text{or} \quad b_2(v) = \frac{pv}{1 + av^q} \]

(1.4)

with \( a > 0, \ p > 0 \) and \( q > 0 \). When \( b(v) = b_1(v) \) with \( q = 1 \), Eq. (1.1) is called the nonlocal Nicholson’s blowflies equation. Lastly, the function \( f_\alpha(y) \) is the heat kernel

\[ f_\alpha(y) = \frac{1}{\sqrt{4\pi \alpha}} e^{-y^2/4\alpha} \quad \text{with} \quad \int_{-\infty}^{\infty} f_\alpha(y) \, dy = 1. \]

(1.5)

By solving the equation

\[ d_m v = \varepsilon p \int_{-\infty}^{\infty} b(v(t - r, x - y)) f_\alpha(y) \, dy, \]

we obtain immediately the two constant equilibria \( v_{\pm} \) of (1.1)

\[
\text{for } b_1(v): \quad v_- = 0 \quad \text{and} \quad v_+ = \left( \frac{1}{a} \ln \frac{\varepsilon p}{d_m} \right)^{1/q},
\]

(1.6)

\[
\text{for } b_2(v): \quad v_- = 0 \quad \text{and} \quad v_+ = \left( \frac{\varepsilon p - d_m}{ad_m} \right)^{1/q}.
\]

(1.7)

When \( \varepsilon p > d_m \), we have \( v_+ > v_- = 0 \).
A traveling wavefront of Eq. (1.1) connecting the constant states \( v_\pm \) is an increasing solution of the form of \( \phi(x + ct) \), where \( c > 0 \) is the wave speed. Thus, it satisfies

\[
\begin{cases}
-c\phi'(\xi) - D_m\phi''(\xi) + d_m\phi(\xi) = \varepsilon p \int_{-\infty}^{\infty} b(\phi(\xi - cr - y))f_\sigma(y)\,dy, \\
\phi(\pm\infty) = v_\pm,
\end{cases}
\]

where \( \xi = x + ct \) and \( \xi' = \frac{d\xi}{dt} \). The existence of such traveling wavefronts was first proved by So, Wu and Zou [23] for \( b(v) = b_1(v) \) with \( q = 1 \) by means of the method of the upper–lower solutions, and later extended by Liang and Wu [12] to the general case \( b(v) = b_1(v) \), or \( b(v) = b_2(v) \). It was proved that there exists a number \( c_* > 0 \), called the critical wave speed (i.e., the minimum speed), such that for \( c > c_* \), the wavefront \( \phi(x + ct) \) exists. The boundedness of the critical wave speed \( c_* \) and the asymptotic behavior of \( c_* \) with respect to the delay time \( r \) and the diffusion rate \( D_m \) were further analyzed by Wu, Wei and Mei [31]. They proved that \( c_* \to 2\sqrt{D_m(\varepsilon p - 2d_m)} \) as \( r \to 0 \), and \( c_* = O(r^{-1/2}) \to 0 \) as \( r \to \infty \), while \( c_* = O(\sqrt{D_m}) \to \infty \) as \( D_m \to \infty \). Then, Mei and So [17] showed that, when the wavefront is as fast as \( c > 2\sqrt{D_m(3\varepsilon p - 2d_m)} \) and the initial perturbation around the wavefront in a weighted Sobolev space is small enough, then the wavefront is asymptotically stable. However, for the gap \( c_* < c \leq 2\sqrt{D_m(3\varepsilon p - 2d_m)} \), the stability of these slower wavefronts remains open. Obviously, as we know, such a stability result for the slower wavefronts is much more significant and challenging from both the mathematical and physical points of view. The purpose of the present paper is to resolve this case.

By using the weighted energy method, as in [16–18], the crucial step is to establish the basic \( L^2 \)-energy estimate for \( v - \phi \). However, different from the case of local nonlinearity in [16], the technique with a piecewise weight function cannot be applied to get the stability for all \( c > c_* \) in the nonlocal case. This is because the nonlocal integral term will produce a large upper bound which forces us to look for a wave with a big enough wave-speed in order to eliminate it (see, for example, the stability result given in [17] with \( c > 2\sqrt{D_m(3\varepsilon p - 2d_m)} \)). Here, we develop a new technique to overcome this difficulty caused by the nonlocality. First of all, we introduce a non-piecewise weight function \( w(x) = e^{-kx} \) for some carefully selected positive number \( k \), which is related to the critical wave speed \( c_* \).

Next we prove that, for any given wave with wave speed \( c > c_* \), the solution \( v(t, x) \) converges to the corresponding traveling wavefront \( \phi(x + ct) \) in the weighted Sobolev space \( H^1_w(R) \). Hence, we have the convergence result: \( \sup_{x \in I} |v(t, x) - \phi(x + ct)| = O(e^{-\mu t}) \) for some positive constant \( \mu \), where \( I = (\infty, \tilde{x}) \) is any interval with \( \tilde{x} \gg 1 \), due to the shortage of \( w(x) \to 0 \) as \( x \to +\infty \). After that, we further prove \( \lim_{x \to +\infty} |v(t, x) - \phi(x + ct)| = O(e^{-\mu t}) \). By combining these two convergence results, we obtain the stability of the wavefront in the whole space \((\infty, \infty)\).

The rest of the paper is organized as follows. In Section 2, we state the existence result for traveling wavefronts. Based on the property of the critical wavefront, we then introduce a weight function which is ideal for our purpose. In Section 3, we combine the weighted energy method with the comparison principle together and prove the stability for all traveling wavefronts \( (c > c_*) \). There will be no restriction on the delay time \( r \), the wave speed \( c \) and the initial perturbation. This essentially improves and develops the previous stability results in [17]. In Section 4, we present some numerical results based on the Crank–Nicholson scheme. These numerical results confirm our theoretical results. Finally, in Section 5, we give a remark on the first part of this series of study [16] that the \( b'(v_+) \ll 1 \) can be removed by our new technique showed in this paper, even so \( b'(v_+) \ll 1 \) is reasonable as explained in [16].

For the notations adopted in the present paper, in particular the weighted Sobolev space \( H^1_w(R) \) as well as the space \( C([0, T]; H^1_w(R)) \), we refer the reader to the first part of this series of study [16].

For other interesting research works related to this topic, please refer to [1–34] and the references therein.
2. Nonlinear stability

In this section, we first state the existence of traveling wavefronts and then introduce the nonlinear stability result for traveling wavefronts.

By using the method of the upper–lower solutions, Liang and Wu [12] (see also the early work by So, Wu and Zou [23]) proved the existence of the traveling wavefronts.

Proposition 2.1 (Existence of traveling wavefronts). (See [12,23].) Assume that

\[ \frac{\varepsilon p}{d_m} < \frac{1}{q}, \]

for \( b(v) = b_1(v) \): \( 1 < \frac{\varepsilon p}{d_m} \leq \frac{1}{q} \) if \( q > 1 \),

or \( 1 < \frac{\varepsilon p}{d_m} < \infty \) if \( 0 < q \leq 1 \).

Then there exist a minimum speed \( c^* = c^*(r, \alpha, \varepsilon, D_m, d_m, p) \in (0, 2\sqrt{D_m(\varepsilon p - d_m)}) \) and a corresponding number \( \lambda_* = \lambda(c^*) > 0 \) satisfying

\[ \Delta(\lambda_*, c^*) = 0, \quad \frac{\partial}{\partial \lambda} \Delta(\lambda_*, c^*) = 0, \]

where

\[ \Delta(\lambda, c) = \varepsilon p e^{\alpha \lambda^2 - \lambda c r} - [c \lambda - D_m \lambda^2 + d_m]. \]

such that for all \( c > c_* \), the traveling wavefront \( \phi(x + ct) \) of Eq. (1.1) connecting \( v_\pm \) exists uniquely (up to shift).

Furthermore, for \( c = c_* \), it holds that \( \Delta(\lambda_*, c) = 0 \), i.e.,

\[ \varepsilon p e^{\alpha \lambda_*^2 - \lambda_* c_* r} = c_* \lambda_* - D_m \lambda_*^2 + d_m, \]

and for \( c > c_* \), it holds that \( \Delta(\lambda_*, c) < 0 \), i.e.,

\[ \varepsilon p e^{\alpha \lambda_*^2 - \lambda_* c r} < c \lambda_* - D_m \lambda_*^2 + d_m. \]

We now define a weight function as

\[ w(x) = e^{-2\lambda_* x}, \]

where \( \lambda_* = \lambda_*(c_*) \) is the positive constant determined in Proposition 2.1. As showed in [31], we know that \( \frac{c_*^2}{2D_m} < \lambda_* < \frac{c_*}{D_m} \). Obviously, it satisfies \( w(x) \to +\infty \) as \( x \to -\infty \) and \( w(x) \to 0 \) as \( x \to +\infty \).

Next, we state our stability result.

Theorem 2.2 (Nonlinear stability). Let \( \frac{\varepsilon p}{d_m} \) satisfy (2.1) for \( b(v) = b_1(v) \), or (2.2) for \( b(v) = b_2(v) \). For any given wavefront \( \phi(x + ct) \) with a speed \( c > c_* \), if \( c \) satisfies

\[ e^{\frac{2\lambda_*^2}{\alpha}} < \frac{c \lambda_* - D_m \lambda_*^2 + d_m}{c_* \lambda_* - D_m \lambda_*^2 + d_m}, \]
the initial data holds
\[ v_- \leq v_0(s, x) \leq v_+ , \quad \text{for } (s, x) \in [-r, 0] \times R, \]
and the initial perturbation is \( v_0(s, x) - \phi(x + cs) \in C([-r, 0]; H^1_w(R)) \), then the solution of (1.1) and (1.2) satisfies \( v(t, x) - \phi(x + ct) \in C([0, \infty); H^1_w(R)) \), and
\[ v_- \leq v(t, x) \leq v_+ , \quad \text{for } (t, x) \in [0, \infty) \times R, \]
and
\[ \| (v - \phi)(t) \|_{H^1_w(R)} \leq Ce^{-\mu t}, \quad t \geq 0, \]
for some positive constant \( \mu \).
In particular, the solution \( v(t, x) \) also converges asymptotically to the wavefront \( \phi(x + ct) \) in the \( L^\infty \)-norm:
\[ \sup_{x \in R} | v(t, x) - \phi(x + ct) | \leq Ce^{-\mu t}, \quad t \geq 0. \]

**Remark 1.**

1. The condition (2.8) is equivalent to
\[ \alpha < \frac{1}{\lambda_1^2} \ln \frac{c\lambda_s - D_m\xi^2 + d_m}{c\lambda_s - D_m\lambda_s^2 + d_m}, \]
where \( \alpha \) is independent of \( c, D_m \), and \( d_m \) but both \( \lambda_s \) and \( c_s \) are related to \( \alpha \). For given \( \alpha \), we need the wave speed \( c \) to be large such as in (2.13). Conversely, when \( c \) is sufficiently large, one can easily verify that \( \frac{1}{\lambda_1^2} \ln \frac{c\xi_s - D_m\xi_s^2 + d_m}{c\lambda_s - D_m\lambda_s^2 + d_m} \) is sufficiently large. This ensures \( \alpha \) is sufficiently large as well. When \( c \) is sufficiently close to the critical wave speed \( c_+ \), then one can recognize that \( \frac{1}{\lambda_1^2} \ln \frac{c\lambda_s - D_m\lambda_s^2 + d_m}{c\lambda_s - D_m\lambda_s^2 + d_m} \ll 1 \), which means \( \alpha \) needed to be sufficiently small. Thus, when \( \alpha \) is small enough, we may obtain the stability for those slower waves with the speed \( c \in (c_s, 2\sqrt{D_m(3\varepsilon p - 2d_m)}) \), which is the unsolved gap in [17]. So, here we improve the previous stability results in [17].

2. The smallness for the initial perturbation and the condition \( b'(v_+) = 0 \) both required in [17] are removed for our new stability result.

3. By a deep analysis on the wavefront \( \phi(x + ct) \), it can be verified that
\[ | \phi(\xi) - v_- | = O(1)e^{-\lambda_1|\xi|} \quad \text{as } \xi \to -\infty, \]
where \( \lambda_1 = \lambda_1(c) > 0 \) is determined by \( \Delta(\lambda_1, c) = 0 \) and satisfies \( 0 < \lambda_1 < \lambda_s \). However, different from the local case studied in [16], the weight function \( w(x) \) cannot be taken as \( w(x) = e^{2\lambda|x|} \) for \( \lambda \in (\lambda_1, \lambda_+) \) as \( x \to -\infty \), namely, the decay rate of the initial perturbation around the wavefront cannot be released to
\[ | v_0(s, x) - \phi(x + cs) | = O(1)e^{-\lambda|x|}, \quad \text{for } \lambda \in (\lambda_1, \lambda_+), \quad \text{as } x \to -\infty. \]
The reason is that the nonlocal term (integration) produces a big upper bound which cannot be eliminated by the weight \( w(x) = e^{2\lambda|x|} \) with \( \lambda \in (\lambda_1, \lambda_+) \) (see (3.29) in the proof of the key Lemma 3.3). That is why here we need to select a stronger weight function as \( w(x) = e^{2\lambda^2|x|} \) for \( x \to -\infty \).
3. Proof of nonlinear stability

As shown in [16] (see also [9,15,27]), one can similarly prove the following boundedness and the comparison principle.

**Lemma 3.1** (Boundedness). Let the initial data satisfy

\[ v_- = 0 \leq v_0(s, x) \leq v_+ \quad \text{for} \quad (s, x) \in [-r, 0] \times R. \tag{3.1} \]

Then the solution \( v(t, x) \) of the Cauchy problem (1.1) and (1.2) satisfies

\[ v_- \leq v(t, x) \leq v_+ \quad \text{for} \quad (t, x) \in [0, \infty) \times R. \tag{3.2} \]

**Lemma 3.2** (Comparison principle). Let \( \bar{v}(t, x) \) and \( v(t, x) \) be the solutions of (1.1) and (1.2) with the initial data \( \bar{v}_0(s, x) \) and \( v_0(s, x) \), respectively. If

\[ v_- \leq v_0(s, x) \leq \bar{v}_0(s, x) \leq v_+ \quad \text{for} \quad (s, x) \in [-r, 0] \times R, \tag{3.3} \]

then

\[ v_- \leq v(t, x) \leq \bar{v}(t, x) \leq v_+ \quad \text{for} \quad (t, x) \in R_+ \times R. \tag{3.4} \]

Let the initial data \( v_0(s, x) \) be such that \( v_- \leq v_0(s, x) \leq v_+ \) for \( (s, x) \in [-r, 0] \times R \), and let

\[
\begin{align*}
V_0^+(s, x) &= \max\{v_0(s, x), \phi(x + cs)\}, \\
V_0^-(s, x) &= \min\{v_0(s, x), \phi(x + cs)\},
\end{align*}
\tag{3.5}
\]

This implies

\[ v_- \leq V_0^-(s, x) \leq v_0(s, x) \leq V_0^+(s, x) \leq v_+ \quad \text{for} \quad (s, x) \in [-r, 0] \times R, \tag{3.6} \]

\[ v_- \leq \bar{V}_0^-(s, x) \leq \phi(x + cs) \leq \bar{V}_0^+(s, x) \leq \bar{v}_+ \quad \text{for} \quad (s, x) \in [-r, 0] \times R. \tag{3.7} \]

Define \( V^+(t, x) \) and \( V^-(t, x) \) as the corresponding solutions of (1.1) and (1.2) with respect to initial data \( V_0^+(s, x) \) and \( V_0^-(s, x) \), respectively, i.e.,

\[
\begin{align*}
\frac{dV^\pm}{dt} - D_m \frac{\partial^2 V^\pm}{\partial x^2} + d_m V^\pm &= \varepsilon \int_{-\infty}^{\infty} b(V^\pm(t-r, x-y)) f_\alpha(y) \, dy, \quad (t, x) \in R_+ \times R, \\
V^\pm(s, x) &= V_0^\pm(s, x), \quad x \in R, \quad s \in [-r, 0].
\end{align*}
\tag{3.8}
\]

By Lemma 3.2, it follows that

\[ v_- \leq V^-(t, x) \leq v(t, x) \leq V^+(t, x) \leq v_+ \quad \text{for} \quad (t, x) \in R_+ \times R, \tag{3.9} \]

\[ v_- \leq V^-(t, x) \leq \phi(x + ct) \leq V^+(t, x) \leq v_+ \quad \text{for} \quad (t, x) \in R_+ \times R. \tag{3.10} \]

As in [16], we also need the following three steps to prove stability.

**Step 1:** The convergence of \( V^+(t, x) \) to \( \phi(x + ct) \).
Let \( \xi := x + ct \) and

\[
\begin{align*}
\xi_0(s, \xi) := V^+_0(s, x) - \phi(x + cs), & \quad \xi(s, \xi) := V^+(t, x) - \phi(x + ct).
\end{align*}
\] (3.11)

Then by (3.6) and (3.9), we have

\[
\xi(t, \xi) \geq 0 \quad \text{and} \quad \xi_0(s, \xi) \geq 0.
\] (3.12)

It can be verified that \( \xi(t, \xi) \) satisfies

\[
\begin{cases}
\frac{\partial \xi}{\partial t} + c \frac{\partial \xi}{\partial \xi} - Dm \frac{\partial^2 \xi}{\partial \xi^2} + Dm \xi - \varepsilon \int_{-\infty}^{\infty} b'(\phi(\xi - y - cr))u(t - r, \xi - y - cr) f_\alpha(y) dy \\
\xi(t, \xi) = \xi_0(s, \xi), \quad (s, x) \in [-r, 0] \times R,
\end{cases}
\] (3.13)

where

\[
Q(t - r, \xi - y - cr) = b(\phi + u) - b(\phi) - b'(\phi)u
\] (3.14)

with \( \phi = \phi(\xi - y - cr) \) and \( \xi = \xi(t - r, \xi - y - cr) \).

Multiplying (3.13) by \( e^{2\mu t} \xi(\xi) \xi(t, \xi) \), one obtains

\[
\begin{align*}
&\left\{ \frac{1}{2} e^{2\mu t} \xi(\xi) \xi(t, \xi) \right\}_t + e^{2\mu t} \left\{ \frac{1}{2} c \xi(\xi)^2 - Dm \xi(\xi) \xi(t, \xi) \right\} + Dm e^{2\mu t} \xi(\xi) \xi(t, \xi) \nonumber \\
&\quad + \left\{ - \frac{c}{2} \frac{\varepsilon}{\varepsilon} + Dm - \mu \right\} e^{2\mu t} \xi(\xi)^2 \\
&\quad - \varepsilon e^{2\mu t} \xi(\xi) u(\xi, t) \int_{-\infty}^{\infty} b'(\phi(\xi - y - cr))u(t - r, \xi - y - cr) f_\alpha(y) dy \\
&\quad = \varepsilon e^{2\mu t} \xi(\xi) u(\xi, t) \int_{-\infty}^{\infty} Q(t - r, \xi - y - cr) f_\alpha(y) dy.
\end{align*}
\] (3.15)

Notice that, by the Cauchy–Schwarz inequality,

\[
|Dm e^{2\mu t} \xi(\xi) \xi(t, \xi) | = Dm e^{2\mu t} \xi(\xi) \xi(t, \xi) \leq Dm e^{2\mu t} \xi(\xi)^2 + \frac{Dm}{4} e^{2\mu t} \left( \frac{\varepsilon}{\varepsilon} \right)^2 \xi(\xi)^2.
\]

then (3.15) is reduced to

\[
\begin{align*}
&\left\{ \frac{1}{2} e^{2\mu t} \xi(\xi)^2 \right\}_t + \left\{ \frac{1}{2} e^{2\mu t} c \xi(\xi)^2 - Dm e^{2\mu t} \xi(\xi) \xi(t, \xi) \right\} \\
&\quad + \left\{ - \frac{c}{2} \frac{\varepsilon}{\varepsilon} + Dm - \mu \right\} e^{2\mu t} \xi(\xi)^2
\end{align*}
\]
\[ -\varepsilon e^{2\mu t} w(\xi) u(\xi, t) \int_{-\infty}^{\infty} b'(\phi(\xi - y - cr)) u(t - r, \xi - y - cr) f_\alpha(y) \, dy \]
\[ \leq \varepsilon e^{2\mu t} w(\xi) u(\xi, t) \int_{-\infty}^{\infty} Q(t - r, \xi - y - cr) f_\alpha(y) \, dy. \]  

(3.16)

Integrating the above inequality over \( R \times [0, t] \) with respect to \( \xi \) and \( t \), one further has

\[ e^{2\mu t} \| u(t) \|_{L^2(w)}^2 + \int_{0}^{t} \int_{R} e^{2\mu \tau} \left\{ -c \frac{w'(\xi)}{w(\xi)} + 2d_{\mu} - \frac{D_{\mu}}{2} \left( \frac{w'(\xi)}{w(\xi)} \right)^2 \right\} w(\xi) u^2(\tau, \xi) \, d\xi \, d\tau \]
\[ -2\varepsilon \int_{0}^{t} \int_{R} e^{2\mu \tau} w(\xi) b'(\phi(\xi - y - cr)) u(\tau, \xi) u(\tau - r, \xi - y - cr) f_\alpha(y) \, dy \, d\xi \, d\tau \]
\[ \leq \| u_0(0) \|_{L^2(w)}^2 + 2\varepsilon \int_{0}^{t} \int_{R} e^{2\mu \tau} w(\xi) u(\tau, \xi) Q(\tau - y - r, \xi - cr) f_\alpha(y) \, dy \, d\xi \, d\tau. \]  

(3.17)

We now turn to estimate the third term in (3.17). First of all, by using the change of variables \( y \mapsto y, \xi - y - cr \mapsto \xi, \tau - r \mapsto \tau \), one can get

\[ \int_{0}^{t} \int_{R} e^{2\mu t} w(\xi) b'(\phi(\xi - y - cr)) u^2(\tau - r, \xi - y - cr) f_\alpha(y) \, dy \, d\xi \, d\tau \]
\[ = \int_{-r}^{t-r} \int_{R} e^{2\mu (\tau + r)} w(\xi + y + cr) b'(\phi(\xi)) u^2(\tau, \xi) f_\alpha(y) \, dy \, d\xi \, d\tau \]
\[ = e^{2\mu t} \int_{0}^{t-r} \int_{R} e^{2\mu \tau} \left[ b'(\phi(\xi)) \frac{w'((\xi + y) + cr)}{w((\xi + y) + cr)} \right] w(\xi + y + cr) f_\alpha(y) \, dy \, d\xi \, d\tau \]
\[ + e^{2\mu t} \int_{0}^{t-r} \int_{R} e^{2\mu \tau} \left[ b'(\phi(\xi)) \frac{w'(\xi)}{w(\xi)} \right] w(\xi + y + cr) f_\alpha(y) \, dy \, d\xi \, d\tau \]
\[ \leq e^{2\mu t} \int_{0}^{t-r} \int_{R} e^{2\mu \tau} \left[ b'(\phi(\xi)) \frac{w'(\xi)}{w(\xi)} \right] w(\xi + y + cr) f_\alpha(y) \, dy \, d\xi \, d\tau \]
\[ + e^{2\mu t} \int_{0}^{t-r} \int_{R} e^{2\mu \tau} \left[ b'(\phi(\xi)) \frac{w'(\xi)}{w(\xi)} \right] w(\xi + y + cr) f_\alpha(y) \, dy \, d\xi \, d\tau. \]  

(3.18)

Using the Cauchy–Schwarz inequality again,

\[ |u(\tau, \xi) u(\tau - r, \xi - y - cr)| \leq \frac{\eta}{2} u^2(\tau, \xi) + \frac{1}{2\eta} u^2(\tau - r, \xi - y - cr) \]  

(3.19)
for a positive constant $\eta$ which will be selected later (see Lemma 3.3 below), and using (3.18) and the fact $b'(\phi) > 0$ (which is proved in [16]), one can estimate the third term in (3.17) as follows:

\[
2\varepsilon \int_0^t \int_{\mathbb{R}} \int_{\mathbb{R}} e^{2\mu \tau} w(\xi) b'((\phi(\xi) - y - cr)) u(\tau, \xi) u(\tau - r, \xi - y - cr) f_\alpha(y) \, dy \, d\xi \, d\tau \\
\leq \varepsilon \int_0^t \int_{\mathbb{R}} \int_{\mathbb{R}} e^{2\mu \tau} w(\xi) b'(\phi(\xi) - y - cr) \left[ \eta u^2(\tau, \xi) + \frac{1}{\eta} u^2(\tau - r, \xi - y - cr) \right] f_\alpha(y) \, dy \, d\xi \, d\tau \\
= \varepsilon \eta \int_0^t \int_{\mathbb{R}} \int_{\mathbb{R}} e^{2\mu \tau} w(\xi) b'(\phi(\xi) - y - cr) u^2(\tau, \xi) f_\alpha(y) \, dy \, d\xi \, d\tau \\
+ \frac{\varepsilon}{\eta} \int_0^t \int_{\mathbb{R}} \int_{\mathbb{R}} e^{2\mu \tau} w(\xi) b'(\phi(\xi) - y - cr) u^2(\tau - r, \xi - y - cr) f_\alpha(y) \, dy \, d\xi \, d\tau \\
\leq \varepsilon \eta \int_0^t \int_{\mathbb{R}} e^{2\mu \tau} w(\xi) \left[ \int_{\mathbb{R}} b'(\phi(\xi) - y - cr) f_\alpha(y) \, dy \right] u^2(\tau, \xi) \, d\xi \, d\tau \\
+ \frac{\varepsilon e^{2\mu r}}{\eta} \int_{-r}^t \int_{\mathbb{R}} e^{2\mu r} \left[ b'(\phi(\xi)) \int_{\mathbb{R}} \frac{w(\xi + y + cr)}{w(\xi)} f_\alpha(y) \, dy \right] w(\xi) u^2(\tau, \xi) \, d\xi \, d\tau \\
+ \frac{\varepsilon e^{2\mu r}}{\eta} \int_{-r}^t \int_{\mathbb{R}} e^{2\mu r} \left[ b'(\phi(\xi)) \int_{\mathbb{R}} \frac{w(\xi + y + cr)}{w(\xi)} f_\alpha(y) \, dy \right] w(\xi) u^2_0(\tau, \xi) \, d\xi \, d\tau.
\]  

Substituting (3.20) into (3.17) yields

\[
e^{2\mu t} \left\| u(t) \right\|_{L_w^2}^2 + \int_0^t \int_{\mathbb{R}} e^{2\mu \tau} B_{\eta, w, w}(\xi) w(\xi) u^2(\tau, \xi) \, d\xi \, d\tau \\
\leq \left\| u_0(0) \right\|_{L_w^2}^2 + \frac{\varepsilon e^{2\mu r}}{\eta} \int_{-r}^t \int_{\mathbb{R}} e^{2\mu r} \left[ b'(\phi(\xi)) \int_{\mathbb{R}} \frac{w(\xi + y + cr)}{w(\xi)} f_\alpha(y) \, dy \right] w(\xi) u^2_0(\tau, \xi) \, d\xi \, d\tau \\
+ 2\varepsilon \int_0^t \int_{\mathbb{R}} e^{2\mu \tau} w(\xi) u(\tau, \xi) Q(\tau - y - r, \xi - cr) f_\alpha(y) \, dy \, d\xi \, d\tau,
\]

where

\[
B_{\eta, w, w}(\xi) := A_{\eta, w}(\xi) - 2\mu - \frac{\varepsilon}{\eta} (e^{2\mu r} - 1)b'(\phi(\xi)) \int_{\mathbb{R}} \frac{w(\xi + y + cr)}{w(\xi)} f_\alpha(y) \, dy
\]

and

\[
A_{\eta, w}(\xi) := -c \frac{w'(\xi)}{w(\xi)} + 2d_m \frac{D_m}{2} \left( \frac{w'(\xi)}{w(\xi)} \right)^2
\]
\[
- \varepsilon \eta \int_{\mathbb{R}} b'(\phi - y - cr)f_\alpha(y) \, dy \\
- \frac{\varepsilon b'(\phi)}{\eta} \int_{\mathbb{R}} \frac{w(\xi + y + cr)}{w(\xi)} f_\alpha(y) \, dy.
\] (3.23)

As shown in [16], by the Taylor's formula and the fact \( b''(v) \leq 0 \) for \( v_- \leq v \leq v_+ \), one can similarly obtain
\[
Q(t - r, x - y) = b(\phi + u) - b(\phi) - b'(\phi)u \leq 0,
\] (3.24)

which leads, with the fact \( u > 0 \) (see (3.12)), that
\[
2\varepsilon \int_{-r}^{t} \int_{\mathbb{R}} \int_{\mathbb{R}} e^{2\mu \tau} w(\xi) u(\tau, \xi) Q(\tau - y - r, \xi - cr)f_\alpha(y) \, dy \, d\xi \, d\tau \leq 0.
\] (3.25)

On the other hand, since \( 0 \leq b'(\phi) \leq \rho \) (see (3.18) in [16]), and \( w(\xi + y + cr) = e^{-2\lambda_\ast(y + cr)} \), it follows that
\[
\varepsilon e^{2\mu_\ast} \int_{-r}^{0} \int_{\mathbb{R}} e^{2\mu \tau} b'(\phi(\xi)) \left[ \int_{\mathbb{R}} \frac{w(\xi + y + cr)}{w(\xi)} f_\alpha(y) \, dy \right] w(\xi) u_0^2(\tau, \xi) \, d\xi \, d\tau
\]
\[
\leq \varepsilon pe^{2\mu_\ast} \int_{-r}^{0} \int_{\mathbb{R}} \left[ \int_{\mathbb{R}} e^{-2\lambda_\ast(y + cr)} f_\alpha(y) \, dy \right] w(\xi) u_0^2(\tau, \xi) \, d\xi \, d\tau
\]
\[
= \varepsilon pe^{2\mu_\ast} \int_{-r}^{0} \int_{\mathbb{R}} \left[ e^{4\alpha \lambda^2 - 2\lambda_\ast cr} \int_{\mathbb{R}} \frac{1}{\sqrt{4\pi \alpha}} e^{-\frac{1}{4\pi \alpha}(x - r)^2} \, dx \right] w(\xi) u_0^2(\tau, \xi) \, d\xi \, d\tau
\]
\[
= \varepsilon pe^{2\mu_\ast + 4\alpha \lambda^2 - 2\lambda_\ast cr} \int_{-r}^{0} e^{2\mu \tau} w(\xi) u_0^2(\tau, \xi) \, d\xi \, d\tau
\]
\[
\leq C \int_{-r}^{0} \| u(\tau) \|^2_{L^2} \, d\tau.
\] (3.26)

Applying (3.25) and (3.26) in (3.21), one then obtains
\[
e^{2\mu_\ast} \| u(t) \|^2_{L^2} + \int_{0}^{t} \int_{\mathbb{R}} e^{2\mu \tau} B_{n, \mu, w}(\xi) w(\xi) u^2(\tau, \xi) \, d\xi \, d\tau
\]
\[
\leq \| u(0) \|^2_{L^2} + C \int_{-r}^{0} \| u(\tau) \|^2_{L^2} \, d\tau.
\] (3.27)

Next, we will carefully select the numbers \( \eta, \mu \) and the weight function \( w(\xi) \) to prove \( B_{n, \mu, w}(\xi) > 0 \). This is the crucial step in the present paper. For that purpose, we need the following key lemma.
Lemma 3.3. Let \( \eta = e^{2\xi^2 \alpha - \lambda_* c} \). Then \( A_{\eta, w}(\xi) \) defined in (3.23) satisfies
\[
A_{\eta, w}(\xi) \geq C_1 > 0, \quad \xi \in R,
\]
for some positive constant \( C_1 \).

Proof. Notice that \( \eta = e^{2\xi^2 \alpha - \lambda_* c}, \ w(\xi) = e^{-2\lambda_* \xi}, \ \frac{w'(\xi)}{w(\xi)} = -2\lambda_* \) and \( \frac{w(\xi + y + cr)}{w(\xi)} = e^{-2\lambda_*(y + cr)} \), as well as \( 0 \leq b'(\phi(\xi)) \leq p \) (see (3.18) in [16]), and \( \int \ f_\alpha(y) \ dy = 1 \). One may obtain
\[
B_{\mu, \eta, w}(\xi) = 2c_\alpha + 2d_m - 2D_m \lambda_*^2 - \varepsilon \eta \int R b'(\phi(\xi - y - cr)) f_\alpha(y) \ dy \\
- \frac{\varepsilon b'(\phi(\xi))}{\eta} \int R e^{-2\lambda_*(y + cr)} f_\alpha(y) \ dy \\
\geq 2c_\alpha + 2d_m - 2D_m \lambda_*^2 - \varepsilon \eta p \int R f_\alpha(y) \ dy \\
- \frac{\varepsilon p}{\eta} e^{4\lambda_*^2 \alpha - 2\lambda_* c} \int R \frac{1}{\sqrt{4\pi \alpha}} e^{-\left(\frac{y}{\sqrt{4\alpha \lambda_*}} + \sqrt{4\alpha \lambda_*}\right)^2} \ dy \\
= 2c_\alpha + 2d_m - 2D_m \lambda_*^2 - \varepsilon \eta p - \frac{\varepsilon p}{\eta} e^{4\lambda_*^2 \alpha - 2\lambda_* c} \\
= 2\left[ c_\alpha + d_m - D_m \lambda_*^2 + \varepsilon p e^{2\lambda_*^2 \alpha - \lambda_* c} \right] \\
= 2\left[ c_\alpha + d_m - D_m \lambda_*^2 + \varepsilon p e^{2\lambda_*^2 \alpha - \lambda_* c} - \varepsilon p \right] \\
= 2\left[ \left( c_\alpha + d_m - D_m \lambda_*^2 + \varepsilon p e^{2\lambda_*^2 \alpha - \lambda_* c} - \varepsilon p \right) - \varepsilon p \right] \\
= \left. C_1 > 0 \right[ \text{by (2.8)}].
\]
The lemma is proved. \( \square \)

Lemma 3.4. Let \( \mu_1 > 0 \) be the unique solution of the equation
\[
C_1 = 2\mu_1 + \varepsilon p \eta(e^{2\mu_1 r} - 1).
\]
If \( 0 < \mu < \mu_1 \), then
\[
B_{0, \mu, w}(\xi) \geq C_2 > 0, \quad \xi \in (-\infty, \infty),
\]
for some positive constant \( C_2 \).

Proof. Applying (3.28) to (3.22), and noting \( 0 \leq b'(\phi) \leq p \) for \( v_- \leq \phi \leq v_+ \), and \( \eta = e^{2\xi^2 \alpha - \lambda_* c} \), it can be verified that
\[
B_{\eta, \mu, w}(\xi) \geq C_1 - 2\mu - \frac{\varepsilon}{\eta} \left( e^{2\mu_1 r} - 1 \right) b'(\phi(\xi)) \int R \frac{w(\xi + y + cr)}{w(\xi)} f_\alpha(y) \ dy
\]
This completes the proof of the lemma. \( \square \)

Below we will derive the basic energy estimates which are crucial for our main stability result.

Applying (3.31) to (3.27), and dropping the positive term \( \int_{0}^{t} \int_{\mathbb{R}} e^{2\mu t} B_{0, \mu, \alpha} w(\xi) u^{2}(\tau, \xi) d\xi d\tau \), one then immediately establishes the first energy estimate as follows.

**Lemma 3.5.** It holds that

\[
e^{2\mu t} \| u(t) \|_{L_{w}^{2}}^{2} \leq C \left( \| u_{0}(0) \|_{L_{w}^{2}}^{2} + \int_{-r}^{0} \| u_{0}(\tau) \|_{L_{w}^{2}}^{2} d\tau \right), \quad t \geq 0.
\]

(3.33)

Furthermore, differentiating Eq. (3.13) with respect to \( \xi \), and multiplying it by \( e^{2\mu t} w(\xi) u_{\xi}(t, \xi) \), and integrating the resultant equation over \( \mathbb{R} \times [0, t] \) with respect to \( \xi \) and \( t \), then by using (3.33) in Lemma 3.5, one can obtain the second energy estimate as follows.

**Lemma 3.6.** It holds that

\[
e^{2\mu t} \| u_{\xi}(t) \|_{L_{w}^{2}}^{2} \leq C \left( \| u_{0}(0) \|_{H_{w}^{1}}^{2} + \int_{-r}^{0} \| u_{0}(\tau) \|_{H_{w}^{1}}^{2} d\tau \right), \quad t \geq 0.
\]

(3.34)

Thus, (3.33) and (3.34) imply the following lemma.

**Lemma 3.7.** It holds that

\[
\| u(t) \|_{H_{w}^{1}}^{2} \leq Ce^{-2\mu t} \left( \| u_{0}(0) \|_{H_{w}^{1}}^{2} + \int_{-r}^{0} \| u_{0}(\tau) \|_{H_{w}^{1}}^{2} d\tau \right), \quad t \geq 0.
\]

(3.35)

Notice that, \( w(\xi) \to 0 \) as \( \xi \to \infty \), we cannot expect \( H_{w}^{1}(\mathbb{R}) \hookrightarrow C(\mathbb{R}) \). However, for any interval \( I = (-\infty, \bar{\xi}] \) for some large \( \bar{\xi} \gg 1 \), we may have the Sobolev’s embedding result \( H_{w}^{1}(I) \hookrightarrow C(I) \), which when combining with (3.35) gives the following \( L^{\infty} \)-estimate.

**Lemma 3.8.** It holds that

\[
\sup_{\xi \in I} |u(t, \xi)| \leq Ce^{-\mu t} \left( \| u_{0}(0) \|_{H_{w}^{1}}^{2} + \int_{-r}^{0} \| u_{0}(\tau) \|_{H_{w}^{1}}^{2} d\tau \right)^{1/2}, \quad t > 0.
\]

(3.36)

for any interval \( I = (-\infty, \bar{\xi}] \) with some large \( \bar{\xi} \gg 1 \).
Next, we need to extend the $L^\infty$-convergence in (3.36) to the whole space $(-\infty, \infty)$. The key step is to prove the convergence at $\xi = \infty$.

Lemma 3.9. It holds that
\[
\lim_{\xi \to \infty} |u(t, \xi)| \leq Ce^{-\mu_2 t}, \quad t \geq 0, \tag{3.37}
\]
where $\mu_2 := d_m - \varepsilon b'(v_+) > 0$.

Proof. As shown in (3.24), i.e., $Q(t - r, x - y) \leq 0$, (3.13) is reduced to
\[
\frac{\partial u}{\partial t} + c \frac{\partial u}{\partial \xi} - D_m \frac{\partial^2 u}{\partial \xi^2} + d_m u - \varepsilon \int_{-\infty}^{\infty} b'(\phi(\xi - y - cr))u(t - r, \xi - y - cr)f_\alpha(y) dy \leq 0. \tag{3.38}
\]
Taking limits as $\xi \to \infty$, and noting that $u_\xi(t, \infty) = 0$, $u_{\xi\xi}(t, \infty) = 0$ due to the boundedness of $u(t, \xi)$ for all $\xi \in (-\infty, \infty)$, one immediately obtains
\[
\frac{d}{dt} u(t, \infty) + d_m u(t, \infty) - \varepsilon b'(v_+)u(t - r, \infty) \int_{-\infty}^{\infty} f_\alpha(y) dy \leq 0. \tag{3.39}
\]
Since $\int_{\mathbb{R}} f_\alpha(y) dy = 1$, therefore
\[
\frac{d}{dt} u(t, \infty) + d_m u(t, \infty) - \varepsilon b'(v_+)u(t - r, \infty) \leq 0. \tag{3.39}
\]
Integrating (3.39) over $[0, t]$, one then has
\[
u(t, \infty) + d_m \int_0^t u(\tau, \infty) d\tau - \varepsilon b'(v_+) \int_0^t u(\tau - r, \infty) d\tau \leq u_0(0, \infty). \tag{3.40}
\]
By the change of variable $\tau - r \rightarrow \tau$ to the third term of (3.40), it follows that
\[
\varepsilon b'(v_+) \int_0^t u(\tau - r, \infty) d\tau = \varepsilon b'(v_+) \int_{-r}^t u(\tau, \infty) d\tau \leq \varepsilon b'(v_+) \int_0^t u(\tau, \infty) d\tau + \varepsilon b'(v_+) \int_{-r}^0 u_0(\tau, \infty) d\tau. \tag{3.41}
\]
Substituting (3.41) into (3.40), we have
\[
u(t, \infty) + \left[d_m - \varepsilon b'(v_+)\right] \int_0^t u(\tau, \infty) d\tau \leq C_3. \tag{3.42}
\]
where
\[
C_3 := u_0(0, \infty) + \epsilon b'(v_+) \int_0^\infty u_0(\tau, \infty) d\tau.
\]

By a straightforward but tedious computation, one can check
\[
\epsilon b'_1(v_+) < d_m \quad \text{and} \quad \epsilon b'_2(v_+) < d_m.
\]
Thus, when \( b(v) = b_1(v) \) or \( b(v) = b_2(v) \), one always has
\[
\epsilon b'(v_+) < d_m.
\]
Then, by the Gronwall's inequality, (3.42) yields
\[
u(t, \infty) \leq C e^{-\mu t},
\]
with \( \mu = d_m - \epsilon b'(v_+) > 0 \). The proof is complete.

Combining (3.37) and (3.38), and letting \( 0 < \mu < \min\{\mu_1, \mu_2\} \), one finally proves the \( L^\infty \)-convergence for all \( \xi \in \mathbb{R} \).

**Lemma 3.10.** It holds that
\[
\sup_{x \in \mathbb{R}} |V^+(t, \xi) - \phi(x + ct)| = \sup_{\xi \in \mathbb{R}} |u(t, \xi)| \leq C e^{-\mu t}, \quad t \geq 0,
\]
where \( 0 < \mu < \min\{\mu_1, \mu_2\} \).

**Step 2:** The convergence of \( V^-(t, x) \) to \( \phi(x + ct) \).

Let \( \xi = x + ct \) and
\[
u(t, \xi) = \phi(x + ct) - V^-(t, x), \quad u_0(s, \xi) = \phi(x + cs) - V^-_0(s, x).
\]
As shown in the above, we can similarly prove that \( V^-(t, x) \) converges to \( \phi(x + ct) \).

**Lemma 3.11.** It holds that
\[
\sup_{x \in \mathbb{R}} |V^-(t, x) - \phi(x + ct)| = \sup_{\xi \in \mathbb{R}} |u(t, \xi)| \leq C e^{-\mu t}, \quad t \geq 0,
\]
where \( 0 < \mu < \min\{\mu_1, \mu_2\} \).

**Step 3:** The convergence of \( v(t, x) \) to \( \phi(x + ct) \).
Since the initial data satisfy
\[
V^-_0(x, s) \leq v_0(x, s) \leq V^+_0(x, s),
\]
by Lemma 3.2, it can be verified that the corresponding solutions of (1.1) and (1.2) satisfy
\[
V^-(t, x) \leq v(t, x) \leq V^+(t, x), \quad (t, x) \in \mathbb{R}_+ \times \mathbb{R}.
\]
Combining (3.44) in Lemma 3.10 and (3.46) in Lemma 3.11, we have the following stability result.
Although the original model assumes the spatial domain is the whole domain, a finite computation implemented. The sizes of the time step and space step are chosen as $\Delta t = 0.04$ and $\Delta x = 0.08$. Although the original model assumes the spatial domain is the whole domain, a finite computational domain ($-L, L$) is imposed. Here, we let $L = 800$, then the computational domain is sufficiently large so that numerical boundary effect is ignorable. In this section, let the birth rate function be $b_1(v) = pve^{-q v}$ with $q = 1$. We report the numerical simulations for four test cases (see Table 1). For simplicity, we first choose $D_m = 1$, $\varepsilon = 1$ and $d_m = 1$; other parameters and the initial data for each case study are listed in Table 1. The final computed time is 120 for Cases 1 and 2, and 300 for Cases 3 and 4.

By using the Crank-Nicholson scheme, we obtain the following numerical results, which also demonstrate the stability of the traveling wavefronts. In Case 1, the delay time is chosen to be small $(r = 0.5)$, and the initial data $v(0, x)$ is within $[v_-, v_+]$. The numerical results show that, after a short time the solution $v(t, x)$ of Eqs. (1.1) and (1.2) behaves as a traveling wave which propagates from right to left with a positive speed $c$ (see Fig. 1). This numerically confirms the stability of the traveling wavefronts.

In Case 2, we still take the delay time small as in Case 1, but choose the initial data to exceed $v_+$ a lot in some points, namely, the initial perturbation around the traveling wavefront should be really large. The numerical computations in Fig. 2 demonstrate that the solution $v(t, x)$ asymptotically behaves like a traveling wave propagating from right to left with a positive speed $c$.
Cases 3 and 4 are to show the stability of wavefronts with a large delay time. At this stage, we take $r = 10$, but the initial data $v_0(s, x)$ is selected as what we did in Cases 1 and 2 before, respectively. The numerical simulations presented in Figs. 3 and 4 show also that, after a short time, the solution $v(t, x)$ always behaves like a traveling wavefront which propagates from left to right with a positive speed $c$. 
Fig. 3. Case 3: for the big delay time $r = 10$ and the initial data within $[v_-, v_+]$, the presented graphs are for the solution $v(t, x)$ at different time $t$, which behave like a stable traveling wavefront.

Fig. 4. Case 4: for the big delay time $r = 10$ and the initial data exceeding $[v_-, v_+]$, the presented graphs are for the solution $v(t, x)$ in different time $t$, which behave like a stable traveling wavefront.
5. Remark

For the local time-delayed reaction–diffusion equation

$$\frac{\partial v}{\partial t} - D_m \frac{\partial^2 v}{\partial x^2} + d_m v = \varepsilon b(v(t-r,x)), \quad (t, x) \in (0, \infty) \times R,$$

(5.1)

the stability has been proved in the first part [16] with a restriction $b'(v_+) \ll 1$, even so it is reasonable as explained in [16]. Such a condition is needed in the stability proof for $x \gg 1$. However, as we know, when $x \gg 1$, $v = v_+$ is the stable node of (5.1). This will be an advantage for the stability proof. By setting the weight function $w(x)$ as (2.7), we can prove a similar result as Lemma 3.9, which leads us to remove the condition $b(v_+) \ll 1$.

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